FROM THE MECHANISMS OF OBSTACLE AVOIDANCE TOWARDS THE PREVENTION OF FALLS

een wetenschappelijke proeve op het gebied
der Medische Wetenschappen

Proefschrift

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CHAPTER 1

GENERAL INTRODUCTION
GENERAL INTRODUCTION

Epidemiology of falls
Falls in the elderly are a major health problem, because of the large numbers and the serious consequences of these falls. It also places an increasing burden on health care resources, because of the growing proportion of elderly in our society. Approximately 30% (O’Loughlin et al., 1993; Tinetti et al., 1988; Tromp et al., 2001) of people over the age of 65 living in the community have been reported to fall at least once a year. This number increases with age and the reported incidence rates are generally higher for women than for men. Falls often have serious consequences. Of all falls in community-dwelling elderly, approximately 10% results in serious injuries, like hip (1-2%) or other fractures (3-5%), or soft tissue injuries (5%) (Campbell et al., 1990; O’Loughlin et al., 1993; Tinetti et al., 1988). In addition, falls do not only have physical, but also important psychosocial consequences, like fear of falling. Fear of falling can lead to a reduction in activity level, which, in turn, can lead to functional decline and social isolation (Tinetti et al., 1994; Vellas et al., 1997).

In the Dutch society, 2.2 million people are 65 years and older (CBS). When the results of a representative Dutch sample of elderly (LASA study, Tromp et al., 2001) are generalized to the whole Dutch population of elderly, the number of people sustaining a fall is more than 650,000, and the total number of falls even exceeds 1 million. Every year, a total of 89,000 elderly visit the emergency department, 28,900 are hospitalized, and more than 1,500 die as a result of a fall incident. The direct medical costs of a fall incident are 3,400 Euro on average (Consument en Veiligheid, CBS).

Prevention of falls
In order to design successful intervention strategies to prevent falls in the elderly, it is necessary to have insight into the causes of falls. In previous research, numerous risk factors for falls have been mentioned (for review, see Bloem et al., 2003). These risk factors can be divided into intrinsic (related to the person) and extrinsic (environmental) factors. Intrinsic factors that have been shown to be clearly associated to increased fall risk are, for example, previous falls, muscle weakness, impaired balance control, use of psychotropic drugs, impaired vision, and medical conditions (e.g. stroke and Parkinson’s disease). Examples of extrinsic risk factors are doorsteps, loose carpets, stairs, slippery floors, inappropriate footwear, and poor lighting. The fall risk increases with the number of risk factors present (Tinetti et al., 1988).

Even with this knowledge, however, intervening on the problem of falls in the elderly is rather complex, because a fall is usually caused by an interaction of multiple risk factors. In the past two decades a wide variety of falls prevention interventions have been investigated that targeted one or more of these risk factors. Most successful in the reduction of fall incidence were exercise programs aimed at balance training and/or muscle strengthening (Day et al., 2002; Province et al., 1995; Robertson et al., 2002). Multifactorial interventions that were based on individual risk factor assessments also proved to be successful in the prevention of fall incidents (Close et al., 1999; Gillespie et al., 2002). Home-visit based elimination of environmental risk factors was not successful (Day et al., 2002; Van Haastregt et al., 2000).
Another approach to prevent falls could be to develop an intervention program that is mainly based on the reported circumstances of falls, instead of being primarily focused on risk factor abatement. Such interventions would typically include elements like obstacle course walking (Liu-Ambrose et al., 2004; Means et al., 1996), because several studies have reported that a large number of falls occurred as a consequence of tripping and stumbling over obstacles while walking (25-50% of all falls) (Berg et al., 1997; Rynnanen et al., 1991; Tinetti et al., 1988). The results of these programs were promising with respect to the reduction of fall risk (Liu-Ambrose et al., 2004) and improvement of functional performance (Liu-Ambrose et al., 2004; Means et al., 1996), but conclusive evidence of the practical effects of these programs on actual falls is lacking. In order to enhance the probability of success of obstacle based intervention programs, it may help to get a better understanding of why elderly fall over obstacles. Experimental studies could provide insight into the specific problems that elderly experience in obstacle avoidance. Two different situations can be identified in obstacle avoidance. The first occurs when the obstacle has not been noticed before the foot hits the obstacle. The resultant stumble has to be overcome successfully in order to maintain an upright position (reactive control). The second situation occurs when the obstacle has been noticed in advance. Proactive adjustments in the locomotor pattern can be made to avoid contact with the obstacle. Both situations have been studied in different experimental setups and a summary of the main findings will be given in the next paragraphs.

Reactive obstacle avoidance

A number of research groups have used experimental setups to evoke or simulate trips in both young and older adults. Compared to young adults, elderly were reported to fall more often as a result of the induced trip (Forner-Cordero, 2003; Pavol et al., 1996). Given this age-related increase of the probability to fall after a trip, the next question would be which mechanism could be responsible. Schillings and co-workers (2005) have investigated whether neural control mechanisms in stumbling reactions showed age-related differences. During treadmill walking, an obstacle was dropped in front of the left leg to evoke a trip in various phases of the gait cycle. The latencies of EMG responses of upper and lower leg muscles after foot contact with the obstacle were studied. In the older subjects, short and medium-latency responses (less than 100 ms after obstacle contact) were prolonged by 6 ms and 10-19 ms, respectively. In addition, the older adults showed smaller responses in ipsilateral upper leg muscles (biceps femoris and rectus femoris) after an early-swing trip. This resulted in a smaller clearance margin of the swing limb over the obstacle, which could have contributed to the observed larger number of failures in clearing the obstacle.

Another mechanism, possibly contributing to the increased probability of falling after a trip has been studied by Pijnappels and co-workers (2005a; 2005b). It concerns age-related limitations in the mechanics and control of the support limb recovery reactions. In their experiments, people were tripped by an obstacle that unexpectedly rose from the ground and blocked the swing limb. Older adults, and particularly those who actually fell as a result of this perturbation, showed smaller rates of ankle, knee, and hip moment generation, as well as smaller peak ankle moments at push-off. This may lead to insufficient arrest of the forward angular momentum resulting from the trip, and a fall can be the result (Pijnappels et al., in press). In a subsequent study, Pijnappels and co-workers (2005a; 2005b) showed that the timing of EMG activity of support leg muscles was only marginally different between young and older adults. From this it was concluded that age-related reduction in the rate of muscle activation development, rather than delayed responses, could contribute to the observed reduced force generation of elderly. The age-related deteriorations in tripping responses that were found in these studies, however, all seem to be fairly ‘hard-wired’, which raises the question whether these mechanisms can be improved by training. So far, no previous studies have investigated the potential benefits of any kind of training on tripping characteristics.

Proactive obstacle avoidance

In proactive avoidance the obstacle is noticed in advance and adjustments in the locomotor pattern will be made in order to avoid contact with the obstacle. A growing number of studies on this kind of obstacle avoidance have studied the differences in performance between young and older adults (Begg and Sparrow, 2000; Chen et al., 1991, 1994a, 1994b, 1996; Hahn and Chou, 2004; McFadyen and Prince, 2002). A distinction can be made between situations in which the obstacle is detected well in advance, and obstacle avoidance at short notice. This distinction is particularly important with respect to the successfullness of avoidance, which may be considered the measure most indicative of obstacle-related fall risk. Obstacle avoidance success rates have been shown to be closely related to the time between obstacle detection and the estimated moment of foot contact with the obstacle (available response time, ART) (Chen et al., 1994b). Only one research group has previously compared obstacle avoidance characteristics in time critical situations between young and older adults. In their experimental setup, Chen and co-workers used a narrow band of light that was projected onto the ground at the position of the estimated next foot landing. They found that both young and older adults were able to successfully avoid an obstacle when there was enough time (ART of more than 500 ms). In both age groups, success rates declined with decreasing ART (Chen et al., 1994b). On average, older adults only needed an additional 30 ms to achieve similar success rates as the young. Because in daily life attention is rarely completely focused on the locomotor task, they also studied obstacle avoidance with divided attention (Chen et al., 1996). As a secondary task, the participants had to perform a vocal reaction time task simultaneous to the obstacle avoidance task. In this dual task condition the difference between young and older adults was much more pronounced. The elderly showed a 32.0% - 35.7% decline of avoidance success rates, compared to only 14.7% – 19.9% in the young.

With respect to characteristics of fixed obstacle avoidance (obstacles detected well in advance), many studies have shown age-related decline in kinetic, kinematic, as well as spatiotemporal measures. Spatial measures (toe-obstacle distance, foot clearance over the obstacle, and heel-obstacle distance) have been mentioned most frequently in relation to safe obstacle negotiation. Only heel distance, however, has been consistently reported to be smaller in older adults than in the young.
Lamoureux and co-workers (2003) have shown that this kind of measure can be improved in the elderly by a strength training program. Whether a training program could also improve success rates of time critical obstacle avoidance is unknown. The meaning of improvements with respect to the risk for falls also remains to be determined. In addition, it is not clear yet which obstacle avoidance parameters are the most important determinants of the successfulness of obstacle avoidance. These issues will be addressed in this thesis, using an approach in which obstacles have to be avoided on a treadmill (Schillings et al., 1996).

From prevention of falls to prevention of fall injuries

Although the emphasis has been mainly on the prevention of falls, the ultimate goal is a reduction of fall related injuries. This is presumed to be a logical result of a reduction in the number of falls. Recently, Robertson and co-workers (2002) confirmed this presumed relation between a reduction in fall incidents and fall related injuries. It is impossible to completely eliminate the occurrence of fall incidents in the elderly, but a reduction is feasible. Interventions aimed at the decrease of fall impact forces may be a next step in order to further reduce the number of fall related injuries. Hip protectors have been shown to prevent fall related hip fractures in nursing homes (Lauritzen et al., 1993), but compliance with the hip protector is usually poor (Van Schoor et al., 2003).

A good alternative could be to teach elderly fall techniques that reduce impact forces. Which techniques are most suitable for elderly, however, is still a matter of debate. A promising approach could be to introduce the practice of martial arts fall techniques to fall preventive interventions. These techniques have been shown to reduce hip impact forces during sideways falling and they do not seem to require considerable muscle strength (Sabick et al., 1999). It is not clear, however, whether elderly people who have not been involved in martial arts can still learn these techniques. Secondly, the working mechanism behind the impact force reduction in martial arts fall techniques has not been determined, yet. In this thesis, a first step will be taken towards an answer to these questions.

Outline of this thesis

The aims of the present thesis were threefold. The first aim was to evaluate the effectiveness of a new falls prevention exercise program for the elderly, which was called the ‘Nijmegen falls prevention program’. This exercise program was developed from the perspective of training in an exercise environment that simulated the most frequently reported circumstances of falls. Walking over a functionally oriented obstacle course, with and without visual restriction or dual tasks, was an important element of this program. The program was not only evaluated in frequently used terms of fall incidence or posturographic measures, but also in terms of obstacle avoidance skills in time-critical conditions.

The second aim of this thesis was to provide more knowledge about the characteristics of obstacle avoidance under time pressure. An obstacle avoidance task on a treadmill was used to determine the parameters relevant to characterize performance on this task, and to determine the influence of dual tasks and advancing age on these parameters.

The third aim of this thesis was to explore whether the practice of martial arts fall techniques, in order to prevent fall injuries, could potentially make a useful addition to the existing exercise regimens. In order to test whether elderly were able to learn these techniques, they were added to the ‘Nijmegen falls prevention program’. In addition, a first set of laboratory fall measurements was performed to get insight into the working mechanism behind the impact force reduction in martial arts falls.

These goals were addressed in the following chapters. In CHAPTER 2, the experimental setup, used for the obstacle avoidance task, is presented. In this setup, participants walked on a treadmill and during various phases of the gait cycle an obstacle could be dropped in front of their left leg. The characteristics of mid-stance, late-stance, and mid-swing obstacle release trials were investigated in young adults both without (single task) and with simultaneous performance of a secondary cognitive task (dual task). In order to determine the effects of this secondary attention-demanding task, success rates, avoidance strategies, and spatiotemporal parameters were compared between single and dual task obstacle avoidance conditions.

In CHAPTER 3, the question is addressed whether young and older females are equally successful and use similar strategies in avoiding obstacles. Obstacles were presented in 10 step cycle conditions, varying from mid-stance to mid-swing. The chosen avoidance strategies were related to a criterion for the selection of foot placement relative to the obstacle position. Avoidance success rates and the distribution of avoidance strategies were compared between young and older females. In CHAPTER 4, it is investigated how fast the first reaction to the obstacle occurred in young adults and whether the choice of an avoidance strategy can be regarded as a voluntary reaction or as more automated behaviour. Latencies of obstacle avoidance reactions were determined and compared to simple reaction times and latencies of voluntary stride modifications. In addition, latencies of two different avoidance strategies (long and short stride strategy) were compared. CHAPTER 5 addresses the question whether the ‘Nijmegen falls prevention program’ was effective in reducing fall incidence rates and improving obstacle avoidance and balance performance. Fall rates, obstacle avoidance success rates, a number of posturographic measures, and a measure of balance confidence were determined in exercise and control group, both before and after the intervention period. Changes over time in these measures were compared between the groups. In CHAPTER 6, the question is posed which obstacle avoidance characteristics are different between young and older adults, and which characteristics are progressively deteriorating with advancing age within a group of elderly. Avoidance success rates, reaction times, the distribution of strategies, and three spatial measures were compared between a sample of young adults and the group of elderly participants of the ‘Nijmegen falls prevention program’ at baseline. Within the latter group, the relation between these measures and age was also determined. In CHAPTER 7, it is investigated on which of these measures, other than success rates, training effects of the ‘Nijmegen falls prevention program’ could be observed. Changes in these measures were determined between the baseline assessment, the assessment after the intervention period and compared between exercise and control group. The events that occurred in the time window from obstacle release to the end of the crossing stride were related to the time span from balance loss to ground impact in case of a fall. Finally, in CHAPTER 8, the reduction of hip impact forces in martial arts fall techniques and the working mechanism behind this reduction were studied.
in experienced fallers (judokas). In order to determine the role of the use of the arm to break the fall, hip impact forces of martial arts fall techniques with and without the use of the arm were determined and compared. The impact forces of martial arts techniques were also compared to those of falls in which the arm is used to block the fall. In addition, hip impact velocities and trunk orientations at impact were calculated and compared between the three fall types.
INTRODUCTION

Attention and performance are closely related. Since the seminal Attention & Performance conferences starting in the late sixties (Sanders and Koster, 1969) numerous cognitive and motor tasks have been used to unravel the intricacies of attentional processes (See e.g. Sanders, 1998). The reverse question, how do attentional processes affect cognitive tasks, has been less frequently studied, while studies about the attentional effects on the evolution of kinematics of motor tasks are even more scarce.

If researchers focused on the attentional demands exerted by or impinged upon motor tasks, they generally concentrated on chronometric effects such as total movement time or average movement velocity. Only a few studies have tried to elucidate the change in kinematic features for the different body segments and/or the temporal phases of a motor task or the related attentional processes to errors, trips and falls. The above applies even more strongly to realistic motor skills like walking, jumping, running, or throwing. A few exceptions are Davis (1983), Adam and Van Wieringen (1988), and Weinberg and Hunt (1976). In the present study we want to further the understanding of how dividing the attention between obstacle avoidance and a cognitive secondary task affects the performance of a natural motor task like walking. For a theoretical perspective, we start from the traditional literature on attentional processes in terms of processing resources. Walking, in contrast to the manifold keying and push button tasks that have been employed in attention and performance research, is a highly automated behavior, and it is not likely that the usual interference patterns that have been found are to be expected in walking while performing a cognitive task (Brown and Carr, 1989). In the present study, the expected kinematic changes of the obstacle avoidance experiments are derived from recent views on the role of biomechanical factors, in particular of stiffness control, in regulating the effects of task stress as well (Van Gemmert and Van Galen, 1997).

Theoretical questions about the relation between attention and performance have frequently been studied by means of the dual task methodology. A well-known model of information-processing underlying the dual task methodology was presented by Kahneman (1973). In this model, the total available processing capacity in humans is limited. The available processing capacity can serve various attentional tasks concurrently, resulting in the desired level of performance for each, provided that the total capacity has not been exceeded. As soon as the capacity is exceeded, performance of at least one task will decline. Additionally Kahneman (1973) introduced the distinction between structural interference and capacity interference. Structural interference occurs when two tasks, which share the same input or output system, overload the capacity of that particular ‘peripheral’ system. Capacity interference occurs when the total central processing capacity has been exceeded by two concurrent tasks. Hence, when dual task methodology is used to study capacity interference, the tasks should be carefully chosen so as not to induce structural interference.

The attentional demands of balance control have been thoroughly studied in the past two decades. It is accepted that in the domain of locomotion and balance control the ability to perform two tasks simultaneously is of vital importance in daily life, since balance control is often accom-
panied by secondary tasks, such as having a conversation while walking. Shumway-Cook et al. (1997) studied the effect of a cognitive task on postural stability in young adults while they were standing quietly on either a firm or a compliant surface. Even in such a simple postural task, increased sway occurred in the dual task condition, indicating that stability was affected by the secondary task. Dual task interference has also been observed in the more difficult tandem Romberg stance (Ken et al., 1985). Localization of attention represents an even higher level of balance control. The demands of balance control appear to have increased in dual task situations. The kinematic parameters that were studied were, for example, toe motion and the stride length (Lajoie et al., 1993, 1996b; Teasdale et al., 1993) and walking (Lajoie et al., 1993, 1996b; Bardy and Laurent, 1991). Within the step-cycle, verbal response times were shorter in the more stable double-support phase than in the less stable single-support phase (Lajoie et al., 1993, 1996b).

All these motor tasks were investigated under stable, undisturbed conditions. Maintenance of balance, however, is often complicated as a result of perturbations or changes in the environment. In daily life, during locomotion one has to deal with targets to be reached or obstacles to be avoided (proactive control of balance) or one has to recover adequately from trips or slips (reactive balance) in order not to lose balance. Brown et al. (1999) studied the attentional demands of postural recovery strategies following an unexpected perturbation. The performance of the secondary task, in this case backward counting, was better when the perturbation had just occurred, indicating the increased attentional demands of reactive postural control. With respect to proactive balance control, Bardy and Laurent (1991) studied participants walking towards a small and a large target. Attentional demands during goal directed walking were greater than in normal walking. The small target condition required most attention. In contrast, in a study by Lajoie et al. (1996a) goal directed walking was not found to be more attentionally demanding, but the primary task of precisely positioning the foot probably required less precision than the primary task of whole body positioning in the study of Bardy and Laurent (1991).

Another example of a proactive balance control task that is proposed to be attentionally demanding is avoiding obstacles while walking. As a single task, obstacle avoidance is studied extensively (Chen et al., 1991; 1994a; Chou and Draganich, 1997, 1998; McFadyen et al., 1991; Patla et al., 1991b; 1992; 1996b; 1999; Patla and Rietdyk, 1993; Patla and Prentice, 1995). The kinematic parameters that were studied were, for example, toe distance, heel distance, toe clearance, and crossing step lengths. In the present study similar measures will be employed to determine dual task effects on the obstacle avoidance task.

The available response time (ART) has been found to be the major determinant of avoidance success rates. Available response time is the time from obstacle occurrence until the foot touches the obstacle when no avoidance reaction is initiated. Secondary obstacle avoidance reactions could be achieved within the step during which the obstacle occurred, but when ARTs decrease, failure rates increase. (Chen et al., 1994b; 1996; Patla et al., 1991b). It has been suggested that the minimum time for successful avoidance might be influenced as a result of biased attention. The probability of an obstacle to occur at a certain place was found to determine the avoidance success rates (Patla, 1997). Previously, there has been only one study of obstacle avoidance under dual task conditions. Chen et al. (1996) investigated the effect of a secondary cognitive task on the performance of an obstacle avoidance task. They found that at available response times of 350 ms, young healthy adults showed a 14.7-19.9% decline in obstacle avoidance scores, whereas they did not show a significant decline when available response times were 450 ms. However, the secondary task consisted of a verbal response to visual stimuli. Since both tasks use the same input system (visual system) the decline of obstacle avoidance scores might have been caused by structural interference rather than capacity interference. During gait tasks in daily life divided attention demands are a reflection of structural interference, for example when looking at the shop windows while walking in a busy shopping street. The situations of daily life in which capacity interference could compromise a gait task are also numerous, like having a conversation while walking or walking in a crowd when useful information is given through an audio system (e.g. in a railway station or supermarket). In fact, those situations in which full attention is being paid to a gait task are quite infrequent.

The aim of the present study is to investigate the nature and temporal change for non-structural dual-task interference during different phases of obstacle avoidance while walking. In designing the secondary task, there were two important considerations. First, in order to exclude the possibility of more peripheral, structural interference, the secondary task should not require the use of the visual system, since this is needed for detection of the obstacle. Therefore, an auditory stimulus was chosen as the input for the secondary task. Secondly, the output of the secondary task was designed so as not to involve the locomotor system, which would thereby interfere with the primary motor task. To avoid the latter type of interference, a verbal response to the auditory stimulus was required. The auditory Stroop task (Cohen and Martin, 1975) meets these criteria and was chosen as secondary task in the present study. We hypothesized that because the Stroop task is highly demanding of general attentional resources, obstacle avoidance would be affected by this cognitive secondary task.

From the point of view of capacity interference it was hypothesized that the dual task under time-critical conditions would result in more failures either in the primary task, or in the secondary task, or in both tasks. The expected dual-task effects on kinematic parameters were derived from stiffness-control theories. Ghaz (1991) has stated that increasing limb stiffness by co-activation of agonist and antagonist muscles provides greater adaptability to unanticipated changes in external forces and loads, and thus unanticipated forces or loads will result in smaller changes in final limb position than if limb stiffness were less as a result of reciprocal activation. Consequently, less attention has to be given to unexpected events that may perturb the limb. When dealing with dual task situations, attention can be reallocated from the primary to the cognitive secondary task by increasing limb stiffness while maintaining acceptable levels of performance on the motor task. In a study on postural control during shoulder width stance and tandem Romberg stance Dault et al. (2001) obtained results indicative of increased stiffness under dual task conditions.
METHODS

Participants
Ten young healthy adults (2 males and 8 females) aged between 21 and 43 years (mean 26.5, sd 6) participated in the experiment. None of the participants suffered from any neurological or motor disorder. They all gave informed consent to participate in the experiment.

Apparatus
The participants walked on a treadmill (Woodway type ERGO EL2) at a speed of 4 km/h, wearing flexible gymnastic shoes. A bridge, to which an electromagnet was attached, was placed above the front of the treadmill (see Schillings et al., 1996; 1999). A wooden obstacle containing a piece of iron, was held by the magnet and could be released by a trigger given by the computer at a preprogrammed delay after left or right heel contact. Heel contact and toe-off were detected by thin insole footswitches (Figure 2). The size of the obstacle was 40.0 by 30.0 by 1.5 cm (length, width, and height, respectively). The height of the obstacle was only slightly larger than the minimal toe clearance during unobstructed gait (Chen et al., 1991; Chou et al., 1997), so horizontal, rather than vertical adaptations in the stride were required. After release, the obstacle always fell in front of the left foot. To prevent the participants from falling they wore a safety harness fixed to an emergency brake on the ceiling. In the event that a participant started to fall, the safety harness would hold her/him and stop the treadmill.

Participants maintained the same location on the treadmill, because deviation in anterior-posterior direction would have resulted in a shift of the phase of the step cycle in which the perturbation was introduced. Participants were therefore instructed to maintain the toe position no more than 10 cm from the obstacle. Participants were given visual feedback about their walking position. They were instructed to check (and correct) their position frequently during the experiment.

Another theory that addresses the role of stiffness under increased task stress (e.g. dual task load) is the neuromotor noise theory as was proposed by Van Galen and co-workers (Van Galen and Van Huygevoort, 2000; Van Gemmert and Van Galen, 1997; 1998). According to this theory, the endpoint variability of a movement should increase as a consequence of increased task stress. This would lead to decreased movement in terms of spatial and temporal precision. In addition, Van Galen and De Jong (1995) have shown in a simulation study on the effects of limb stiffness that spatial movement precision may be enhanced by increasing the stiffness of the moving limb by co-activation of agonist and antagonist muscles. Experimental support for this role of muscle co-activation has been obtained during graphical aiming tasks (Van Gemmert and Van Galen, 1997; 1998; Van Galen and Van Huygevoort, 2000).

Based on the stiffness control theories, it was hypothesized that the main dual task effect would be found with respect to swing limb velocities. The leg during swing can be regarded as a double pendulum, moving mainly by passive forces (Mochon and McMahon, 1980). It has been shown by Patla and Prentice (1995) that during obstacle avoidance this model remains applicable in general, as adaptations of the swing limb trajectory are achieved by passive rather than active forces. When, as a result of the dual task load, co-contraction of both flexor and extensor muscles of the hip and knee occurs, friction in both axes of rotation (hip and knee joint) increases. If one assumes that the contribution of agonist muscle forces to the swing limb trajectory remains equal, the swing limb velocity in forward direction is expected to decrease.

In order to investigate the nature and extent of dual-task interference during obstacle avoidance while walking, failure rates on the avoidance task, choice of avoidance strategy, and kinematic parameters (Figure 1) were assessed in a single and dual task situation and for various temporal relations between a falling obstacle and the momentaneous phase of the step cycle.
**Experimental protocol**

Before the experiment started, the participants were given time to get accustomed to walking on the treadmill. After the participants were able to walk without hand support and when they reported walking comfortably, 32 preliminary trials were performed in order to determine three delays after heel contact for obstacle release. The three delays were chosen in order to result in three different step cycle conditions, with their own specific demands.

![Figure 3](image)

(a) The events in conditions 1, 2, 3-LSS, and 3-SSS are shown, from the beginning of the step before the obstacle falls until the end of the step after the crossing step. The stick diagrams are reconstructed from PC-reflex data with intervals of 140 ms. The moment at which the obstacle fell is indicated by the bold printed stick figure. The obstacle is represented by the black horizontal bar.

(b) Trajectory of the ipsilateral toe in the sagittal plane for conditions 1, 2, 3-LSS, and 3-SSS. The toe trajectories of the most characteristic trials are shown. The dashed line indicates the moment at which the obstacle appeared. The crossing swing phase is printed in bold. The obstacle is represented by the black horizontal bar.

In condition 1, the obstacle fell when the ipsilateral leg was approximately in the mid-swing phase. The participants would have to quickly shorten their ipsilateral stride in order to avoid stepping into the obstacle. During this condition available response times (ARTs) were short and failures, due to contact of the toes with the front of the obstacle, were expected. In condition 2, the obstacle fell when the ipsilateral leg was in early to mid stance. The subject would only have to slightly increase step length and height in order to successfully avoid the obstacle, as it was positioned within the normal swing phase of the ipsilateral leg. No failures were expected in this condition, as ARTs were long. In condition 3, the obstacle fell during late stance of the ipsilateral leg. Because of this position of the foot relative to the obstacle, condition 3 introduced the choice between two possible avoidance strategies: the long stride strategy (LSS) and the short stride strategy (SSS). In the LSS the participants crossed the obstacle by means of an elongated stride, in the SSS the participants made a shortened precrossing stride (i.e. the stride prior to the crossing stride, Figure 1). The failures in this condition were expected to be due to contact of the heel with the obstacle, caused by insufficient lengthening of the crossing stride.

The experimental procedure incorporated 30 trials of obstacle avoidance as a single task (15 minutes) and 30 trials of obstacle avoidance in combination with a secondary cognitive task (dual task, 15 minutes). During either task, the obstacle was released ten times at each of the three chosen delays. The order of the delays was randomly distributed among the thirty trials. Hence, the participants could not predict when the obstacle would fall. During both tasks, participants were required to look at the approaching obstacle and they were instructed, after the obstacle fell, to step over the obstacle with their left foot without touching it. They were requested not to step aside from the obstacle with their left (ipsilateral) foot. During the dual task, the participants also performed the auditory Stroop task (Cohen and Martin, 1975). This secondary, attention demanding task consisted of listening to the words ‘high’, spoken at a high or a low tone, and ‘low’, spoken at a high or a low tone in random order. Hence, the meaning of the word could be or could not be in conflict with the pitch of the tone. The tone conditions were presented in random order. The participants had to report by voice at which tone (high or low) the word was spoken. The order of two tasks was counterbalanced across participants. In this way, the chance that practice effects would bias the analysis of the effect of the dual task was minimized. The effects of the cognitive secondary task on the changes in anticipatory and further motor reactions to the falling object in the primary walking task were also studied.

A marker was attached to the participant’s skin at the trochanter major of the femur, the lateral side of the calcaneus and the fifth metatarsal. The distance between the center of the marker on the fifth metatarsal and the top of the hallux was measured. A fourth marker was placed on top of the obstacle. The positions of the markers were recorded by a two-camera motion analysis system (Qualisys) at a sample rate of 50 Hz. The accuracy of the system was estimated by performing two measurements of the same 20 markers, randomly placed in the calibrated area. The estimated error of the system was 0.22 mm. The whole experiment was recorded on video tape (25 Hz).
Data analysis
The videotapes were analyzed to determine trials during which the ipsilateral foot touched the obstacle (failure trials), and types of chosen strategies were scored from the videotape, as well as the performance on the Stroop task. Rates of LSS chosen in condition 3 and failure rates (number of failures divided by total number of trials) were calculated for each participant.

From the 3-D recordings, a number of kinematic parameters were derived (Figure 1): (a) toe distance, (b) maximum ipsilateral toe height during the crossing swing phase, (c) heel distance, (d) ipsilateral heel-to-heel pre-crossing stride length, (e) ipsilateral heel-to-heel crossing stride length, (f) crossing swing duration, and (g) horizontal crossing swing velocity, calculated as crossing stride length divided by swing duration. Mean values for these parameters were calculated for each participant per condition per task.

Stance lengths were normalized with respect to the control stride length. The stride before the obstacle fell was taken as the control stride. Available response times (ART) were calculated for each trial as a control variable. The ART was the time span between the moment that the obstacle was released and the moment when the toes would have passed the front of the obstacle if no alteration of the stride were made (Figure 4).

Failure rates and rates of LSS chosen in condition 3 were compared for both tasks by paired t tests. Because the nature of the failures in condition 1 and 3-LSS is expected to be very different, two separate paired t tests were performed. Subsequently, all failure trials were excluded from further analysis regarding the kinematic parameters. To test the hypothesis of increased limb stiffness during the dual task, horizontal swing velocity was analyzed, as well as its components swing duration and crossing stride length. Toe height was analyzed to ascertain that the calculation of horizontal crossing swing velocity was not compromised by different toe heights. For condition 3 the dominant strategy of each participant was included in the analysis.

To make sure that no unanticipated dual task effects were missed, pre-crossing stride lengths, toe distances, and heel distances (Figure 1) were analyzed as well. Analysis was performed by 2 x 3 (Task x Condition) repeated measures analyses of variance (ANOVAs). An alpha level of .05 was used for all statistical tests. To determine the effects of the dual task on movement trajectory, the mean horizontal heel displacement during the crossing swing phase (toe-off to heel-on) in condition 1 and condition 2 was calculated for both tasks. For condition 3 no mean trajectory was calculated, as the moment of the first response to the obstacle was initiated during swing (Figure 3a), which differed per participants.

RESULTS

After analysis of the videotapes, a total of 580 trials were selected for further analysis. In total 20 trials were excluded. Seven trials from the single task and thirteen trials from the dual task were excluded for further analysis. Fourteen trials were excluded for technical reasons, such as problems with data sampling or markers being loose. Four trials were excluded because the participant did not follow the instructions. Two trials were excluded because the participant was clearly distracted during the single task. Error rates on the secondary task were less than 10% for all subjects.
Choice of avoidance strategy

For condition 3 the choice of avoidance strategy was analyzed, since, in contrast to the other conditions, two possible strategies, a long stride strategy (LSS) and a short stride strategy (SSS) were used to avoid the obstacle. The LSS was chosen in 72% of all trials in both the single task and the dual task.

Kinematic parameters

During the dual task, horizontal swing velocity was significantly less than during the single task, $F(1,9) = 53.009, p < .001$. Analysis of toe heights yielded no significant dual task effect, $F(1,9) = 0.226, p = .646$, thus horizontal swing velocity was not compromised by dual task-effects on toe heights. Figure 6 shows mean heel displacement trajectories in a-p direction for both single and dual task for conditions 1 and 2. In both conditions at each point of time the dual task trajectory was lagging behind the single task trajectory. With respect to condition 1, Figure 6(a) shows that the crossing stride length was slightly less and that swing duration was slightly greater during the dual task as compared to the single task, which explains the significantly less horizontal swing velocity. With respect to condition 2, Figure 6(b) shows that the crossing stride length was approximately equal for both tasks but that swing duration was greater during the dual task than during the single task.

Table 1. Percentages of total swing trajectory lengths at the corresponding relative phases of swing

<table>
<thead>
<tr>
<th>Moment during swing phase</th>
<th>Early (20%)</th>
<th>Mid (50%)</th>
<th>Late (80%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Task</td>
<td>% of swing trajectory in condition 1</td>
<td>% of swing trajectory in condition 2</td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>13.0</td>
<td>42.0</td>
<td>80.5</td>
</tr>
<tr>
<td>Dual</td>
<td>12.5</td>
<td>41.5</td>
<td>80.0</td>
</tr>
<tr>
<td>Single</td>
<td>12.5</td>
<td>42.0</td>
<td>80.6</td>
</tr>
<tr>
<td>Dual</td>
<td>12.7</td>
<td>42.6</td>
<td>82.0</td>
</tr>
</tbody>
</table>

In order to determine whether the differences between both trajectories were due to scaling or to on-line modifications, normalized trajectories were calculated for condition 1 and condition 2. The trajectories were normalized with respect to both stride length and swing duration. The normalized trajectories revealed some differences between the single and the dual task, though differences were small. In table 1 the total swing trajectory that was traveled at 3 moments during swing: early (20% of swing duration), mid (50% of swing duration), and late swing (80% of swing duration) is shown. The largest difference was observed in condition 2. At 80% of total swing duration, 82.0% of the swing trajectory was covered during the dual task, while during the single task 80.6% of the trajectory was covered. Hence, during the latest 20% of swing duration less of the total trajectory was traveled in the dual task than in the single task. This means that the dual task did not equally affect the various phases of swing.

Analysis of both components of horizontal swing velocity, i.e. swing
duration and crossing stride length, yielded no significant dual task effects and no significant Task x Condition interactions. No significant dual task effects were found with respect to precrossing stride lengths, toe distances, and heel distances. Mean values and standard deviations of the parameters are presented in Table 2 for each condition and each task.

Table 2. Mean values and standard deviations of the kinematic parameters during the single and the dual task.

<table>
<thead>
<tr>
<th>Condition</th>
<th>1</th>
<th>2</th>
<th>3-LSS</th>
<th>3-SSS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Task</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>7.8 ± 6.0</td>
<td>43.0 ± 10.1</td>
<td>71.0 ± 8.0</td>
<td>9.6 ± 5.8</td>
</tr>
<tr>
<td>Dual</td>
<td>8.8 ± 6.1</td>
<td>43.7 ± 9.1</td>
<td>72.5 ± 6.3</td>
<td>10.7 ± 8.7</td>
</tr>
<tr>
<td><strong>Max. toe height (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>20.2 ± 9.5</td>
<td>16.3 ± 4.9</td>
<td>17.9 ± 6.2</td>
<td>16.1 ± 3.2</td>
</tr>
<tr>
<td>Dual</td>
<td>19.3 ± 6.0</td>
<td>16.1 ± 3.3</td>
<td>17.0 ± 4.9</td>
<td>17.8 ± 4.0</td>
</tr>
<tr>
<td><strong>Heel distance (cm)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>41.0 ± 9.6</td>
<td>17.9 ± 7.4</td>
<td>6.1 ± 4.3</td>
<td>48.6 ± 9.9</td>
</tr>
<tr>
<td>Dual</td>
<td>38.4 ± 10.1</td>
<td>17.5 ± 7.2</td>
<td>5.9 ± 5.0</td>
<td>40.0 ± 9.9</td>
</tr>
<tr>
<td><strong>Normalized precrossing stride length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>0.96 ± 0.05</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0.61 ± 0.07</td>
</tr>
<tr>
<td>Dual</td>
<td>0.96 ± 0.05</td>
<td>N.A.</td>
<td>N.A.</td>
<td>0.59 ± 0.08</td>
</tr>
<tr>
<td><strong>Normalized crossing stride length</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>0.97 ± 0.07</td>
<td>1.10 ± 0.06</td>
<td>1.26 ± 0.07</td>
<td>1.05 ± 0.06</td>
</tr>
<tr>
<td>Dual</td>
<td>0.95 ± 0.09</td>
<td>1.10 ± 0.05</td>
<td>1.26 ± 0.06</td>
<td>0.97 ± 0.09</td>
</tr>
<tr>
<td><strong>Swing duration (ms)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>448 ± 42.0</td>
<td>491 ± 53.3</td>
<td>632 ± 77.6</td>
<td>458 ± 54.3</td>
</tr>
<tr>
<td>Dual</td>
<td>453 ± 52.1</td>
<td>505 ± 48.6</td>
<td>636 ± 85.3</td>
<td>447 ± 44.3</td>
</tr>
<tr>
<td><strong>Horizontal swing velocity (m/s)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single</td>
<td>2.61 ± 0.19</td>
<td>2.69 ± 0.15</td>
<td>2.40 ± 0.17</td>
<td>2.78 ± 0.18</td>
</tr>
<tr>
<td>Dual</td>
<td>2.53 ± 0.19</td>
<td>2.61 ± 0.13</td>
<td>2.37 ± 0.17</td>
<td>2.68 ± 0.15</td>
</tr>
</tbody>
</table>

**DISCUSSION**

The aim of the present study was to determine the nature of dual-task interference on obstacle avoidance during walking using a cognitive secondary task in young healthy adults. It was hypothesized that more failures in avoiding the obstacle would occur when attention was divided than when participants could fully concentrate on avoiding the obstacle. In particular under time critical conditions more failures were expected. The failure rates in condition 1 (ART 120-480 ms) of the dual task were 10.8 % greater than during the single task. All failures occurred because of insufficient shortening of the precrossing stride, resulting in toe contact with the obstacle. The increase of the failure rates during the dual task in a time critical condition seems comparable to the results of Chen et al. (1996), despite the different method used for distraction and the different obstacle conditions. They found that at an ART of 350 ms the failure rates of young adults increased by between 12.6 and 17.1 % when attention was divided, depending on the type of distraction, whereas when the ART was 450 ms, the failure rates increased by only between 2.6 and 7.3 %.

In the interpretation of dual task interference on biomechanical parameters, the underlying biomechanical explanation can be found in graphical aiming task studies under dual task stress (Van Gemmert and Van Galen, 1997; 1998; Van Galen and Van Huygevoort, 2000), in which an increase in limb stiffness was measured. The anticipated dual task effect with respect to the kinematic parameters was a decrease of horizontal swing velocity, which was confirmed by the results of the present study. Differences were small, but very consistent, both across participants and across conditions. It might be argued that, because only the horizontal velocity was calculated, differences between the single and the dual task with respect to the total length of the swing trajectory can play a role as well. No differences between tasks were found in maximum toe heights, it therefore seems unlikely that the total length of the foot trajectory would have been different.

The next question is whether the crossing swing trajectory during the dual task was simply a scaled version of the trajectory during the single task or that on-line modifications were responsible for the differences between both trajectories. The present study shows that the swing trajectory during obstacle avoidance was modified on-line, as the various phases of the crossing swing trajectories were not equally affected by the dual task (Table 1). In condition 2, when the stride is lengthened to cross the obstacle, the last 20% of the crossing swing distance during the dual task required more time as compared to the single task. Possibly, the preparation for landing an elongated stride is more attentionally demanding and therefore more affected than the other phases of swing. The finding in the present study that the spatio-temporal progression of the crossing swing trajectory during the dual task could be modified on-line shows us that the motor program for obstacle avoidance is not a rigid program. After initiation of the obstacle avoidance motor program, the central nervous system still has access to this motor program, which permits adaptations to sudden changes in avoidance requirements. Similar results were obtained by Perry and Patla (2001), who observed on-line adjustments of swing limb trajectories to suddenly changing obstacle heights. For stumbling reactions on-line modifications have been found as well (Schillings et al., 2000).

Increased stiffness by co-activation of agonist and antagonist muscles plays a role in the execution of motor tasks under dual task conditions (Dault et al., 2001; Van Gemmert and Van Galen, 1997; 1998; Van Galen and Van Huygevoort, 2000). The question arises whether increasing swing limb stiffness provides an adequate method of dealing with dual task stress in obstacle avoidance tasks. In postural tasks increased stiffness reduces the amplitude of body sway induced by an unanticipated perturbation (Ghez, 1991), thereby decreasing the probability that the centre of pressure will exceed the base of support and reducing the risk of falling. In contrast, increased stiffness of a limb during swing might be a disadvantage if there were the possibility of tripping. The displacement of the swing limb as a result of the stumble will probably be reduced by...
increased stiffness, but the impact of the stumble on the higher body segments (head and trunk) will increase. The upper body will be accelerated in the anterior direction which could lead to forward falling.

During the dual task only a few errors were made on the Stroop task, with more errors being made in the primary task. This seems unusual since failing an obstacle avoidance task might put the participant at risk for loss of balance. It would be expected that, given the nature of the task, the primary task would be prioritized. The obstacle, however, probably was not threatening enough, as it was only slightly higher than the minimal toe clearance during unobstructed gait and it provided a stable surface to land on. Foot contact with the obstacle in any given way could hardly induce a fall accident, and even if loss of balance would have occurred, the safety harness would have prevented the participant from falling. This explanation is in line with the interpretation of results in the study on postural control in which the “posture first” hypothesis was not found to apply during a dual task (Shumway-Cook et al., 1997). It was suggested that in situations where the primary task does not provide a potential threat to stability, priority would be given to the secondary task. This might explain the observation in the present study that the primary task was affected rather than the secondary task.

Although obtained on young adults, the results of the present study are relevant with regard to elderly. Elderly persons have frequently been reported to have more difficulties in performing both a postural task and a cognitive task simultaneously than younger adults (Brown et al., 1999; Chen et al., 1996; Maylor and Wing, 1996; Mulder et al., 1995; Shumway-Cook et al., 1997; Stelmach et al., 1990). Both reduced processing capacity and inadequate allocation of resources between concurrent tasks are thought to play a role (Teasdale, 1991). In the present study young adults were shown to have increased obstacle avoidance failure rates during the dual task, indicating capacity interference given the nature of the Stroop task. Reduced processing capacity in elderly subjects would probably result in greater increases of failure rates than in young adults when performing the same task. In daily life, a frequently occurring event like obstacle avoidance while walking and having a conversation simultaneously might, therefore, put elderly at risk for loss of balance (Lundin-Olsson et al., 1997). Inadequate allocation of resources may add to this risk. If the elderly in dual task situations were to generally increase stiffness, unexpected contacts to obstacles while walking could easily lead to trips and falls. The present study has to be extended to a population of healthy elderly persons in order to estimate the nature and extent of dual-task interference of a cognitive secondary task upon obstacle avoidance while walking in the elderly and to estimate the increased fall risk of elderly of such a dual task.

INTRODUCTION

Avoidance of obstacles while walking is a frequently occurring event in every day life. Successful avoidance of an obstacle requires proactive modulation of the ongoing walking pattern. This is an important motor skill that prevents us from stumbling over the obstacle and from consequent falls. In community-dwelling elderly people, slipping and tripping over obstacles is responsible for 59% of the fall incidents (Berg et al., 1997). A better insight into age-related difficulties in obstacle avoidance could help to diminish the number of fall incidents.

The characteristics of obstacle avoidance have been studied extensively for young adults. Both kinetic and kinematic parameters have been described and the activation patterns of the various muscles involved in the avoidance reaction have been revealed (Chen et al., 1991, 1994a, 1994b; Chou and Draganich, 1997, 1998; McFadyen et al., 1993; McFadyen and Winter, 1991; Patla et al., 1991b, 1992, 1996b, 1999; Patla and Prentice, 1995; Patla and Rietdyk, 1993). The time between obstacle detection and the estimated moment of foot contact with the obstacle (available response time, ART) has been shown to be the major determinant for successful avoidance. Decrease in available response times leads to a reduction of success rates (Chen et al., 1994b, 1996; Patla et al., 1991b, Weerdesteyn et al., 2003). At available response times of 450 ms and more, success rates of close to 100% are achieved (Chen et al., 1994b, 1996; Patla et al., 1991b, Weerdesteyn et al., 2003). This means that an avoidance reaction can be planned and executed within one step.

In obstacle avoidance, two distinct avoidance strategies can be identified, the long step strategy (LSS) and the short step strategy (SSS; Chen et al., 1994a). In an LSS avoidance reaction, the obstacle is crossed by means of a lengthened crossing step. In an SSS avoidance reaction, the pre-crossing step is shortened and the obstacle is crossed in the next step. Chen et al. (1994a) found that the number of SSS reactions increased with decreasing ARTs. However, not only ARTs determine the choice of an avoidance strategy. Patla et al. (1999) performed a study to examine what determines the choice of alternate foot placement with respect to an undesirable landing area in young adults during overground walking. The main criterion for the selection of alternate foot placement was proposed to be minimisation of displacement of the foot from its original landing position (hereafter referred to as minimal displacement criterion). When more than one strategy satisfies this criterion, foot placement in the plane of progression is preferred over medio-lateral displacement. When, within the plane of progression, both lengthening and shortening satisfy the minimal displacement criterion, lengthening is preferred over shortening. Hence, not only ART, but also prediction of future foot placement and constraints imposed by dynamic stability were shown to be important factors in the perception-action coupling of obstacle avoidance.

Only a few studies have been performed to examine whether obstacle avoidance behavior differs between young and older persons. In the most recent one, Hahn and Chou (2004) reported that the elderly showed greater caution in obstacle crossing. This confirmed the previous data from Chen et al. (1991), who showed that the elderly avoided a fixed obstacle in a more conservative way, as indicated by slower crossing.
OLDER WOMEN STRONGLY PREFER STRIDE LENGTHENING TO SHORTENING IN AVOIDING OBSTACLES

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OLDER WOMEN STRONGLY PREFER STRIDE LENGTHENING TO SHORTENING IN AVOIDING OBSTACLES

When avoiding a virtual obstacle at short notice (ARTs from 200 to 450 ms), the success rates of the elderly were slightly smaller than those of young adults. The elderly needed only 30 ms more to achieve the same success rates as young adults did (Chen et al., 1994b). In another study, Chen et al. (1994a) showed that with short ARTs (300 ms) older participants more often used an SSS than did young participants, though this difference was not significant. In this study, differences in control stride lengths between young and older participants were not corrected for, so the moment in the step cycle at which the obstacle was presented was not the same for young and old. Secondly, the virtual obstacle, which was a band of light, was always projected at the estimated landing spot of the leading foot. With this approach, the ratio between the amount of step lengthening required for successful LSS and the amount of step shortening required for successful SSS remains equal at each ART. Therefore, the spatial trade-off as to which strategy (LSS or SSS) will satisfy the minimal displacement criterion is the same in each trial. When the spatial trade-off is the same for each trial, each participant will probably exhibit a strong preference for either LSS or SSS as the dominant strategy. This dominant strategy is expected to be the same at each ART and no transition from one strategy to the other would be expected with decreasing ARTs.

For young adults, Patla et al. (1999) showed that the participant’s systematic dominant strategy in a given foot-obstacle configuration becomes even more dominant when ARTs decrease. The interpretation of this observation was that the decision and selection of an avoidance strategy did not significantly add to the time needed to make the visuo-motor transformation. There are several indications that decision-making in visuo-motor tasks is negatively affected by age. In another experiment by Patla et al. (1996a), both young and older adults were asked to go either over or around obstacles of varying heights that were placed in the travel path. Young adults showed a clear transition point from going over low obstacles to going around higher obstacles based on the height of the obstacle as a proportion of their leg length. The majority of the older adults, however, selected one strategy for all conditions. This stereotyped behavior was proposed to be due to the elimination of decision-making, which would reduce the demands on the cognitive system. Age related problems in decision-making have also been shown by Lord et al. (2003). In a choice stepping reaction time (CSRT) task, they found that the decision component (time from cue to onset of movement) of the stepping response in older adults was prolonged as compared with young adults. Interestingly, the decision components were also found to be longer in fallers than in non-fallers and to be an independent predictor of future falls (Lord and Fitzpatrick, 2001). Additional support for the involvement of age related cognitive decline in the aetiology of falls has been provided by several studies using dual task paradigms (Chen et al., 1996; Lundin-Olsson et al., 1997).

The CSRT task showed age related difficulties in the initiation of a movement from a static position, but the question asked here is whether age would also have adverse effects on decision-making during ongoing movements, like obstacle avoidance at short notice. In order to determine whether there are age-related differences in the choice of an avoidance strategy, the position of the obstacle with respect to the estimated landing spot of the foot should be varied, like in the study of Patla et al. (1999). The dominant strategy in each foot-obstacle configuration can then be compared between young and old. In the present study, obstacle avoidance was studied during treadmill walking. The first aim of the study was to investigate whether the minimal displacement criterion would also apply to the avoidance of a physical obstacle during treadmill walking. The second aim was to determine whether young and older females use the same avoidance strategies. During various phases of the step cycle an obstacle was presented and the observed strategy was related to a measure of minimal displacement. It was hypothesized that the young females would behave according to the minimal displacement principle. The older females were expected to be more stereotypical in their behavior and to prefer one dominant strategy throughout all conditions.

METHODS

Participants

Ten young females aged between 19 and 32 and ten older females aged between 65 and 78 participated in the study. The older females were recruited from elderly sports groups and thus were mostly active elderly. Although both males and females participated in these groups, only females were willing to participate in the present study and this was the only reason for restricting the selection to females. None of the participants suffered from any neurological or major disorder. They all gave informed consent to participation in the study. The study was approved by the local medical ethics committee.

Experimental protocol

The participants walked on a treadmill (ENRAF Nonius, Type EN-tred Rea) at a speed of 4 km/h, wearing flexible shoes (Figure 1a). A gait speed of 4 km/h was chosen, because it was within the range of velocities of free pace walking of both young and older females (Perry, 1992). A bridge, to which an electromagnet was attached, was placed above the front of the treadmill (see Schillings et al., 1996; 1999; Weerdesteyn et al., 2003). A wooden obstacle containing a piece of iron, was held by the magnet and could be released by a trigger given by the computer. The size of the obstacle was 40.0 by 30.0 by 1.5 cm (length, width, and height, respectively). The height of the obstacle exceeded only slightly the minimal toe clearance height during unobstructed gait (Chen et al., 1991; Chou and Draganchik, 1997), so adaptations of stride length were required in combination with minor vertical adaptations. After release, the obstacle always fell in front of the left foot. To prevent the participants from falling they wore a safety harness fixed to the ceiling. Two markers (diameter 5 cm) were attached to the heel and hallux. A third marker (diameter 4 cm) was placed on top of the obstacle. Marker positions were recorded by a six-camera 3-D motion analysis system (Primas) at a sample rate of 100 Hz.

Before the experimental procedure was started, the participants had an opportunity to get accustomed to treadmill walking. During the experiment, marker position recordings were real-time processed. Heel strike was defined by reversal of the heel marker velocity in an anterior direction in combination with the velocity in downward direction that equaled zero.
Algorithms, based on heel strike moment and position, as determined by the heel marker position recordings, were used to predict the normal landing position. Based on this information the exact moment at which the obstacle had to be dropped to achieve a given step cycle condition was determined. The obstacle was not released until a regular walking pattern was achieved, defined as less than 50 ms difference in stride duration between two consecutive strides. The obstacle was dropped at one of ten different moments during the step cycle, equidistantly distributed from mid stance to mid swing of the left leg. These moments were chosen in order to create a wide range of normal landing positions relative to the obstacle. When the obstacle was dropped during mid stance, the LSS was expected to be preferred strongly, because the required stride shortening for successful avoidance was smaller than the required stride shortening. The SSS was expected to be preferred strongly when the obstacle was dropped during mid swing, because in this situation the required shortening was smaller than the required lengthening. The transition between the strategies was expected to take place during late stance to early swing obstacle release conditions. Each step cycle condition was repeated six times, randomly divided across five series of 12 trials. The total experimental procedure consisted of 60 trials. Participants walked at a fixed position, so that the most anterior position of the toes was at a distance of approximately 10 cm to the obstacle prior to its release. Participants were requested to avoid the approaching obstacle. They could achieve this by either shortening (SSS, see Chen et al. (1994a)) or lengthening (LSS) of the stride. Stepping aside from the obstacle with the left foot was not allowed.

Data analysis
During the experiments it was noted whether the trial was successful or unsuccessful, as defined by contact of the left foot with the obstacle. The selected strategy during each trial was determined from the marker position recordings.

In order to quantify the minimal displacement criterion (Patla et al., 1989), the following parameters were determined from the marker position recordings. The normal stride length (heel strike to heel strike) was determined. The obstacle was not released until a regular walking pattern was achieved, defined as less than 50 ms difference in stride duration between two consecutive strides. The obstacle was dropped at one of ten different moments during the step cycle, equidistantly distributed from mid stance to mid swing of the left leg. These moments were chosen in order to create a wide range of normal landing positions relative to the obstacle. When the obstacle was dropped during mid stance, the LSS was expected to be preferred strongly, because the required stride shortening for successful avoidance was smaller than the required stride shortening. The SSS was expected to be preferred strongly when the obstacle was dropped during mid swing, because in this situation the required shortening was smaller than the required lengthening. The transition between the strategies was expected to take place during late stance to early swing obstacle release conditions. Each step cycle condition was repeated six times, randomly divided across five series of 12 trials. The total experimental procedure consisted of 60 trials. Participants walked at a fixed position, so that the most anterior position of the toes was at a distance of approximately 10 cm to the obstacle prior to its release. Participants were requested to avoid the approaching obstacle. They could achieve this by either shortening (SSS, see Chen et al. (1994a)) or lengthening (LSS) of the stride. Stepping aside from the obstacle with the left foot was not allowed.
50% were selected for further analysis.

For each valid trial the ART was determined from the marker position recordings. The ART was defined as the time span between the moment when the obstacle was released and the moment when the toes would have passed the front of the obstacle had no avoidance reaction taken place (Figure 1c). Because the walking position relative to the obstacle was held constant, there was a linear relation between ART and Δ-SS. ART decreased with increasing Δ-SS. Therefore, increasing numbers of failure trials were expected with increasing Δ-SS.

In order to determine whether obstacle avoidance strategies of young and older females were different, the valid trials were divided into ten Δ-SS categories. Each Δ-SS category had a range of 10% of control stride lengths. For both age groups the total numbers of LSS, SSS, and failure trials in each Δ-SS category were counted. Chi-square analyses were carried out for the successful trials of each Δ-SS category in which both LSS and SSS were observed.

Analysis was also performed to determine whether avoidance success rates were different between young and older females. ARTs were divided into categories with a range of 50 ms each. For both age groups the success rates were calculated by dividing the number of successful trials by the total number of trials in each ART category. Chi-square analyses were carried out to determine differences in success scores between the age groups. If any expected frequency in the chi-square analysis was less than 5, Fisher’s exact test was performed alternatively. The alpha level of 0.05 was corrected for the number of tests performed.

RESULTS

The mean normal stride lengths were calculated from the control strides. The mean stride lengths of the young and older females were 1.20 m and 1.13 m, respectively, which was significantly different (Student’s t test, \(p = 0.023\)). The required lengthening was defined as the distance between the expected landing position of the heel if no avoidance reaction were to take place and the rear side of the obstacle, normalized with respect to the control stride length (see Figure 1a). Because the size of the obstacle was the same for all participants while the stride length differed, the required lengthening over all trials was on average 2% larger for the older females than for the young females (Student’s t test, \(p < 0.005\)). The required shortening was defined as the distance between the expected landing position of the hallux if no avoidance reaction were to take place and the front of the obstacle, normalized with respect to the control stride length (see Figure 1a). The required shortening over all trials was the same for both age groups (Student’s t test, \(p = 0.29\)).

In each of the age groups, 503 trials were between –50% and 50% D-SS and SSS were therefore selected for further analysis. The numbers of LSS, SSS, and failures are presented in Table 1.

The success rates of both young and older females are shown in Figure 2. Analyses for age related differences were carried out for five categories of ART (alpha level of 0.01). Success rates differed significantly between the age groups when ARTs were short (< 350 ms). Differences in the success rates of young and older females were 48% in the ART category of 150 to 200 ms (\(X^2 = 23.16, p < 0.001\)) and 38% in the category of 200 to 250 ms (\(X^2 = 24.60, p < 0.001\)). In the category of 250 to 300 ms, the difference was 16%, which was also significant (\(X^2 = 6.78, p = 0.009\)). In the four ART categories between 300 ms and 500 ms no age related differences were observed. For both groups success rates of 100% were observed when the ART was 400 ms or more.

The Δ-SS was defined as the difference between required lengthening and required shortening. The distribution of LSS, SSS, and failures for each Δ-SS category of young females is shown in Figure 3a, while that for older females shown in Figure 3b. The young females had a preference for the LSS up to the Δ-SS category of 0%-10%, while their preference switched towards the SSS in the subsequent category (10%-20%). For the older females this switch point was less obvious. When only the successful trials were considered, the first category in which the SSS was preferred over the LSS was from 30% to 40%. In order to analyze the age related differences, chi square analysis or Fisher’s exact test was carried out for each of the categories in which both strategies were observed. In seven categories both LSS and SSS were observed and analysis for differences in strategies (exclusive of failures) between the age groups was performed (alpha level of 0.007). In the Δ-SS categories of –20% to –40%
OLDER WOMEN STRONGLY PREFER STRIDE LENGTHENING TO SHORTENING IN AVOIDING OBSTACLES

The Δ-SS category of 30%–40% was the most extreme category in which successful LSS were observed. Six LSSs were observed in the older females, while one was observed in the young females. In these particular cases the obstacle started to fall between very late stance and mid swing of the left leg. The required lengthening was between 42% and 52% of the control stride length. Required shortening was between 8% and 17% of the control stride length. During these extreme performances, balance was lost in two trials of the older females. No falls could occur since they were held upright by the safety harness. In one of these trials the older female avoided the obstacle by means of a jump. In one of these trials the older female avoided the obstacle by means of a jump. The observed age-related differences in avoidance strategies could have been biased by different proportions of unsuccessful LSS and SSS in the two age groups. Hence, the same chi-square procedure was repeated with successful strategies and unsuccessful strategies combined. In Figure 4a and 4b for every trial the performed or attempted strategy is shown. Analysis of successful strategies and attempted strategies combined could be performed for eight categories (alpha level of 0.006). In the Δ-SS categories between −50% and −10% there were no age-related differences. In the Δ-SS categories of −10% to 20% the young females performed or attempted the SSS significantly more often than did older females (χ² between 13.59 and 26.17, p < 0.001). In the Δ-SS categories of 20%–30% and 30–40% the young females also showed larger proportions of SSS than the older females, but due to the corrected alpha level, this difference was no longer significant (χ² = 3.81, p = 0.05 and Fisher’s exact, p = 0.05, respectively). The Δ-SS category of 40–50% also failed to show a significant age-related difference (Fisher’s exact, p = 0.11).

DISCUSSION

In previous research, minimisation of displacement of the foot from its original landing position was proposed to be the major criterion for the choice of alternate foot placement in young adults (Patla et al., 1999). The aim of the present study was to investigate whether this minimal displac-
The failure trials distribution of strategies of younger females corresponded for a large part to the minimal displacement criterion. In the present study, the chosen avoidance strategies of young females, either young or old, have been observed (Chen et al., 1991, 1994a, 1994b, Chou and Draganich, 1997, 1998; McFadyen et al., 1993; McFadyen and Winter, 1991; Patla et al., 1991b, 1992, 1996b, 1999; Patla and Prentice, 1995; Patla and Riethy, 1993). In the studies on avoidance strategies by either Patla et al. (1999) and Chen et al. (1994a) both males and females were tested, but no gender difference in strategies was reported. Hence, the results of the present study are likely to be representative for males as well, though this requires experimental confirmation.

In the present study a wide range of foot-obstacle configurations was randomly presented to the participants. This required a new spatial trade-off during each trial. In contrast to the young females, the older females did not switch between LSS and SSS from trial to trial. The strategy of choosing the LSS for the majority of trials is not very efficient spatially, but it minimizes the process of decision-making. The strong preference for one dominant strategy that was observed in the older females could not be expected from the reports of stereotyped locomotion and obstacle avoidance behavior of older adults (Winter, 1991; Patla et al., 1996a). In addition, the elderly have been shown to have increased decision times as compared with the young adults in a choice stepping reaction time task (Lord et al., 2003). The results of the present study provide an additional indication that decision-making in motor tasks is adversely affected by age. Given the observation that the older females chose one strategy for the majority of trials, why would they prefer the LSS to the SSS? It may be argued that the ART was too short for the elderly females to implement the SSS. However, while the study of Chen et al. (1994a) showed the elderly to be capable of successful use of SSS when ARTs (300 ms) were similar to the ARTs of the LSS category 0%-10% in the present study, we did not observe a single SSS in this category. In the study of Chen et al. (1994a), the elderly even exhibited more SSS than LSS reactions at these ARTs, so the ART cannot explain the small number of SSSs in the older females.

The LSS preference of the older females was not likely to be efficient with respect to energy expenditure, either. Varraine et al. (2000) showed that for the same amount of stride length modification, shortening required a 3% increase in muscle activation, while lengthening required only 32%. Chen et al. (1994a) noted that the hip flexion moment required for lengthening exceeded the knee flexion moment required for shortening, because of the difference in leg and shank inertias. Therefore, efficiency can hardly explain the different choice of strategy of the older females.

The LSS may be preferred from the perspective of safety. During normal walking the center of mass (COM) travels anterior to the center of pressure (COP) during the second half of the swing phase. The forward momentum is controlled by the consecutive foot contact, which lies well anterior of the COM. In the situation of stride shortening, the COM travels anterior to the COP in the early stage of the swing phase, and the only way to control dynamic stability is by quick placement of the contralateral foot. The study of Chen et al. (1994a) demonstrated the potential fall risk of stride shortening, as actual falls were observed in situations where a virtual obstacle was avoided by extremely shortened strides. On the other hand, in the present study loss of balance in the lateral direction was observed in two out of six extremely lengthened strides. Hence, when taken to the extremes, the LSS proves to be risky as well.

A second possible explanation as to why the LSS was the preferred strategy of the older females is provided by the differences between young and older persons in the walking pattern during unobstructed gait. The elderly were shown to have larger horizontal heel velocities at heel contact, reduced power absorption of the knee prior to heel contact, and later and lower EMG activity of the hamstrings during late swing (Winter, 1991). Stride shortening is mainly achieved by additional activity of the hamstring muscles, which quickly decelerate the leg during swing to prevent...
pare for early foot contact. When horizontal heel velocity of the elderly during late swing is larger than in young adults, more activity of the hamstring muscles will be required to brake the forward movement of the leg in order to achieve the same amount of stride shortening. Yet the elderly have delayed and decreased hamstrings bursts (Winter, 1991), and in addition, Varraine et al. (2000) have shown that stride shortening is not achieved by a re-organization of EMG patterns, but rather by extra EMG activity superimposed on the normal EMG activity. Hence, later hamstring activation in the unobstructed gait of the elderly would also mean later extra activation for stride shortening. These mechanisms would make it much more difficult for the elderly to shorten their strides. In agreement with this hypothesis, decreased and delayed activity of m. biceps femoris in the elderly has also been demonstrated for stumbling reactions (Schillings et al., 2000).

Finally, not only the motor component of this perception-action coupling task, but also the sensory component could contribute in explaining age related differences in the choice of avoidance strategy. Age related deterioration in visual acuity might play a role in the preference for the LSS. The choice for an LSS at short ARTs would provide more time to perceive the exact boundaries of the obstacle and to actually see the foot landing in relation to the obstacle. In addition, age-related deterioration in lower extremity proprioception may make visual control of foot landing even more desirable.

In conclusion, the minimal displacement criterion explained the behavior of young females very well, but was not sufficient to fully explain the choice of strategy of older females. The stereotyped obstacle avoidance behavior of the older females most likely reflects the difficulty in decision-making during this motor task. The preference for the LSS to the SSS may be related to safety considerations, but it may also be related to age-related changes in the unobstructed gait pattern or deterioration of vision. Further studies, focused on the various possible explanations, could reveal the mechanisms involved in the extreme preference of the elderly for the LSS and provide insight into the relation of the different strategies to the risks of falling.

In daily life, many obstacles are encountered and have to be avoided while walking. If the obstacle remains unnoticed, a trip and possibly a fall will be the result. In most cases, however, the obstacle will have been noticed by the visual system and in response, the locomotor pattern will be adjusted pro-actively in order to avoid the obstacle. It has been shown that these adjustments are fast, as they can be implemented in the normal walking pattern within one step cycle (Chen et al., 1994a; 1994b; Patla et al., 1999; Weerdesteyn et al., 2003). But how fast are they exactly and how does the latency of these responses compare with voluntary reaction times?

This is an important issue, because the answer could provide more insight into the processes involved in this perception-action coupling. In previous studies, the choice of an avoidance strategy has been a topic of interest (Chen et al., 1994b; Patla et al., 1999; Weerdesteyn et al., 2001). The latency of these reactions could indicate whether they can be regarded as voluntary choices or as more automated behavior. Obstacle avoidance requires a response to a visual stimulus. Latencies during simple visual reaction time tasks start from approximately 200ms and the latency increases when more than one response can be triggered during choice reaction time tasks (e.g., Carson et al., 1995). Typically, these responses are obtained from a stationary starting position. However, obstacle avoidance reactions are different in that they do not require initiation of a movement from a stationary starting position. The reaction to the obstacle is characterized by modulation of an ongoing movement. Alstermark et al. (1984) found that cats needed only 70-120 ms to adjust their reaching trajectories when the target was displaced unexpectedly. For humans, latencies of 100-140 ms have been reported for changing the direction of reaching movements (Brenner and Smeets, 2003; Carlton, 1981; Day and Brown, 2001; Day and Lyon, 2000; Paulignan et al., 1990; 1991; Prablanc and Martin, 1992; Soechting and Laquani, 1983; Zelaznik et al., 1983). For both cats and humans, evidence is growing that subcortical pathways are involved in these fast reactions (Day and Brown, 2001;Perfiliev et al., 2003).

With respect to the lower limb, Patla et al. (1991a) studied modification of stepping trajectories. In their study, the participants stepped over an obstacle and sometimes a second obstacle occurred behind the first. They had to traverse the two within the same step by additional lengthening. The participants changed their stepping trajectories about 120 ms after presentation of the second obstacle. The initial trajectory modification was the same for a high and a low second obstacle. After another 120 ms the low and high obstacle trajectories started to deviate. The proposed explanation for these fast responses was that the first response is a general response to the presence of the obstacle, which is fine tuned later on the basis of the properties of the obstacle. This seems to be a reasonable explanation when a response in only one direction is possible, which is additional lengthening of the step. If the responses could be in two directions, lengthening or shortening, it is conceivable that latencies differ.

The aim of the present study was to determine the latencies of obstacle avoidance reactions during treadmill walking. Both lengthening and shortening of the stride could be chosen in order to avoid the obstacle.
Latencies of obstacle avoidance reactions to lengthening and shortening were compared. In addition, these latencies were compared with those obtained after voluntary stride lengthening and shortening following a visual cue. Finally, in the same subjects, the classic simple reactions times of the hand and the foot were measured with the participants at rest and compared to latencies of obstacle avoidance reactions.

**METHODS**

**Participants**

Twenty-five young adults (4 men, 21 women) aged between 20 and 37 participated in the study. None of the participants suffered from any neurological or motor disorder. All participants performed the obstacle avoidance task (OA), while 12 of these participants also performed 3 additional tasks: voluntary stride modifications, a simple reaction time (SRT) task of the foot (SRT foot) and a simple reaction time task of the hand (SRT hand). They all gave informed consent to participate in the study. The study was approved by the local medical ethics committee.

**Experimental setup and protocol**

The participants walked on a treadmill (ENRAF Nonius, Type EN-tred Rea) at a speed of 3 km/h, wearing flexible gymnastic shoes (figure 1a). The gait speed of 3 km/h was chosen because this study was part of a larger study, in which a comparison between young and older people will be made. For the older people, 3 km/h is a comfortable walking speed (Elble et al., 1991; Finley et al., 1969). A bridge, to which an electromagnet was attached, was placed above the front of the treadmill (see Schillings et al., 1996; 1999). A wooden obstacle, containing a piece of iron, was held by the magnet and could be released by a trigger given by the computer. The size of the obstacle was 40.0 by 30.0 by 1.5 cm (length, width, and height, respectively). The height of the obstacle was only slightly larger than the minimal toe clearance during unobstructed gait (Chen et al., 1991; Chou and Draganich, 1997), so adaptations of the stride length were required rather than vertical adaptations.

After release, the obstacle always fell in front of the left foot. Two markers (diameter 3 cm) were attached to the left (ipsilateral) heel and halluc. A third marker (diameter 3 cm) was placed on top of the obstacle. Marker positions were recorded by a 6-camera 3-D motion analysis system (Pivitmas®) at a sample rate of 100 Hz. These positions were processed in real time and an algorithm was used to determine heel strike. Stride times (heel strike to heel strike) were calculated. Next, heel strike moment and position were estimated from the marker positions of the previous strides and the correct moment of obstacle release was calculated. The obstacle was released after at least 5 unperturbed strides were taken from the start of the trial and when the difference between two consecutive strides was less than 50 ms. The reason for this criterion was that stride regularity was a prerequisite for precise timing of obstacle release, which was necessary in the present experimental procedure. Hence, obstacle release did not occur after a fixed number of strides, but depended on the regularity of the walking pattern. In addition, an accelerometer was placed on top of the foot, proximal to the metatarsal joints. Foot accelerations in 3 directions were measured at a sample rate of 2400 Hz.

Each participant performed 30 obstacle avoidance trials, divided over 3 series of 10 trials. Participants were instructed to keep walking at a position, at which the most anterior position of the toes had a distance of approximately 10 cm to the obstacle prior to its release. The obstacle was dropped at 6 different phases during the step cycle, which varied from mid stance to mid swing. These moments were randomly divided over the 3 series. Two of the moments of obstacle release (10 trials) were just before and right after toe off of the ipsilateral leg. In many young adults obstacle release at the transition from stance to swing corresponds to the moment at which they switch from long stride strategy (LSS) towards short stride strategy (SSS; Weerdesteyn et al., 2005). These moments (10 trials) were used to determine the latency of the avoidance reaction. The other phases (20 trials) were introduced to prevent that the participants could predict the moment of obstacle release with respect to the step cycle. These trials were not further analyzed. A control experiment was performed to rule out the role of auditory information on OA latencies. The sound of the obstacle falling onto the treadmill could provide auditory information. Five subjects performed the normal experimental procedure.
and the same procedure when hearing was blocked. Hence, 10 trials per condition per participant were analyzed. Differences between mean latencies of both conditions were tested by means of paired t test and there was no significant difference between both conditions (mean latency 111.2 ms vs 111.4 ms with and without auditory information, respectively, SD of the difference 6.1 ms, \( p = 0.95 \)). Hence, the participants showed no benefit from the presence of auditory information.

For the voluntary stride modifications the same experimental setup was used. The participants wore Plato Spectacles (Portable Liquid Apparatus for Tachistoscopy via visual Occlusion) that could be switched from transparent to translucent by a signal given by the computer. The output signal to the spectacles was recorded by the computer. First the LSS and SSS were practiced as a reaction to the obstacle. Each strategy was practiced at least 10 times. The participants were instructed to keep these movements in their minds and were told that they had to make the same movements (both LSS and SSS) during the task without the obstacle. The moment at which the obstacle started to fall was defined as the moment when the z-position of the obstacle marker during the avoidance stride was 1 mm below the mean z-position minus one standard deviation. Next, the acceleration signal was filtered (second order Butterworth, cut off frequency 75 Hz.). The acceleration in the z-direction (perpendicular to the foot in the sagittal plane) was differentiated for all the control swing phases. The mean and standard deviation of the differentiated signals were calculated. The first observable reaction to the approaching obstacle was defined as the moment at which the differentiated acceleration curve of the avoidance swing phase exceeded the mean ± 2 standard deviations of the control swing phases. The latency was the time span between this moment and the moment when the obstacle started to fall (Figure 2). For each participant, the median latency was used for analysis, because outlying high values occurred more frequently than outlying low values.

To quantify lengthening and shortening latencies in response to the Plato spectacles, the moment at which the trigger was given was determined from the recorded output signal to the spectacles. The accelerometer signals were analyzed in the same way as described for the obstacle avoidance task. The median values for both lengthening and shortening were used for analysis.

For the simple reaction time task of the foot, the recorded output signal to the Plato Spectacles was taken as the moment at which the spectacles became translucent. The first kinematic response was defined as acceleration in z-direction larger than baseline value plus 2*sd, which is analogous to the determination of the kinematic response in the OA task. The average median latency of the OA reaction was determined for all 25 participants. In order to determine whether choosing between two strategies adds to the time needed to react to the obstacle, the population was divided in 3 groups. One group used only the LSS (\( n = 3 \)) in response to the obstacle and the second group used only the SSS (\( n = 8 \)). The third group consisted of participants who used both strategies (\( n = 14 \)). Median latencies of each participant in these three groups were compared by one-way ANOVA. To determine whether LSS reactions were equally as fast as SSS reactions, median latencies of both LSS and SSS reactions were determined for the participants in the group that used both strategies (\( n = 14 \)). Paired t test was conducted to compare between these reactions. The mean height (z-position) and standard deviation of the obstacle marker during the control stride was calculated. The moment at which the obstacle started to fall was defined as the moment when the z-position of the obstacle marker during the avoidance stride was 1 mm below the mean z-position minus one standard deviation.
strategies. It was also tested whether there was a difference in latencies between late stance and early swing obstacle release trials. For all participants ($n = 25$), median latencies of the late stance and the early swing obstacle release condition were compared by paired $t$ tests. For those 12 participants who also performed the voluntary stride modifications, median latencies of lengthening and shortening reactions were also compared by means of paired $t$ test, as well as latencies of late stance and early swing cue conditions.

In order to analyze whether latencies of reactions during the four tasks were different, a repeated measures ANOVA was conducted. For this analysis, the twelve participants who performed all 4 tasks were included and the median latency of each task of each participant was used. Post hoc paired $t$ tests were performed to determine which tasks were significantly different. In order to determine whether there was a relation between latencies of the OA task and latencies of the other tasks, correlation coefficients were determined. An alpha level of .05 was used for all statistical analyses.

RESULTS

For the analysis of OA latencies, a total of 238 trials could be selected in which obstacle release occurred during late stance or early swing. The average median latency of the obstacle avoidance reaction for all subjects was 122 ms ($SD = 14$ ms). In order to investigate whether choosing between two strategies adds to the time needed to react, the groups that used only one strategy (LSS, $n = 3$; SSS, $n = 8$) were compared to the group that used both strategies ($n = 14$). The mean latency was 117 ms ($SD = 10$ ms) in the LSS group, while it was 121 ($SD = 16$ ms) in the SSS group and 124 ms ($SD = 14$ ms) in the two-strategy group (Figure 2). There was no significant difference between these groups ($F(2, 22) = 0.39$, $p = 0.68$).

Figure 2 is an example of a participant who used both strategies. The accelerometer signal of an LSS is shown in Figure 2a, while the signal of an SSS is shown in Figure 2b. The accelerometer signals were clearly different from the onset of the deviation, but the latencies were very similar. In this analysis the group that only used the LSS did not differ from the group that only used the SSS, but power was limited as there were only 3 participants in the LSS group. However, the comparison between median latencies of LSS ($mean = 123$ ms, $SD = 16$ ms) and SSS ($mean = 125$ ms, $SD = 15$ ms) reactions in the group that used both strategies yielded no significant difference either ($p = 0.70$). There was no significant difference in latencies of late stance ($mean = 123$ ms, $SD = 11$ ms) and early swing ($mean = 122$ ms, $SD = 17$ ms) obstacle release trials ($p = 0.98$).

A total of 121 trials could be selected for the analysis of voluntary stride lengthening and shortening. Trials were excluded if the visual cue did not occur during late stance or early swing, if the participant did not follow the instruction correctly (e.g. shortening of the stride when lengthening was required), or if no clear reaction could be observed. For 2 participants, no correct voluntary stride shortening trials could be selected for analysis. Hence, in order to determine whether latencies of lengthening reactions were different from those of shortening reactions, analysis was conducted for the remaining 10 participants. The median latency of both lengthening and shortening was 204 ms ($SD = 31$ ms and 15 ms, respectively). There was no significant difference between the latencies of both reactions ($p = 0.95$). Therefore, for each participant the median over both tasks (lengthening and shortening in response of the Plato Spectacles) was used in the subsequent analyses. The median latency in the late stance cue condition was 205 ms ($SD = 27$ ms) and 195 ms ($SD = 18$ ms) in the early swing cue condition. There was no significant difference between latencies of reactions in both phases of cueing ($p = 0.25$).

A repeated measures ANOVA was conducted to analyse whether there were differences between the latencies of the four different experimental conditions, which were obstacle avoidance, voluntary stride modifications, SRT hand, and SRT foot. There was a main effect of condition ($F(3, 9) = 120.15$, $p < 0.001$). Post-hoc analysis revealed that the OA latency (119 ± 14 ms) was significantly shorter than the latencies of voluntary stride modifications (205 ± 21 ms, $p < 0.001$), SRT foot (179 ± 14 ms, $p = 0.001$), and SRT hand (218 ± 20 ms, $p < 0.001$, Figure 3). There was also a significant difference between the latencies of SRT foot and SRT hand ($p < 0.001$). No significant correlations were present between the latencies of the OA reactions and those of the other tasks (Table 1).

<table>
<thead>
<tr>
<th>Task</th>
<th>Voluntary stride mod</th>
<th>SRT Foot</th>
<th>SRT Hand</th>
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<tbody>
<tr>
<td>Obstacle Avoidance</td>
<td>$r = 0.12$</td>
<td>$r = 0.40$</td>
<td>$r = 0.09$</td>
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<tr>
<td></td>
<td>$p = 0.70$</td>
<td>$p = 0.19$</td>
<td>$p = 0.78$</td>
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DISCUSSION

The aim of the present study was to compare the latencies of obstacle avoidance reactions with different types of voluntary reactions. The results showed that the swing trajectory in response to the sudden occurrence of an obstacle could be modified very quickly and that this reaction was not dependent on the phase of obstacle release. The mean latency of OA reactions was 122 ms. Obstacle avoidance reactions were nearly 100 ms faster than voluntary stride modifications. OA latencies were also shorter than simple reaction times of the hand and the foot. Simple reaction times of hand and foot were significantly different, but the visual cues and the response criterion were not the same in both tasks. Hence, it can not be
excluded that the differences in latencies between SRT hand and SRT foot may partly be explained by the differences in methodology. This was the first study to compare latencies of these various reaction tasks in the same participants.

The results of Patla et al. (1991a), who examined the lower limb trajectory during stepping movements, showed many similarities to the present study, while the methods used differed. The participants started from a standing position and stepped over an obstacle. In some cases, a second obstacle was presented behind the first, in such a way that the stepping trajectory had to be modified. The first kinematic responses to the second obstacle were observed 120 ms after obstacle presentation. This observation is very similar to the results of the present study, despite the differences in task constraints. In the study of Patla et al. (1991a) the participant knew where the second obstacle would occur and that they had to lengthen their step in response to this obstacle. In contrast, in the present study the participants did not know in which phase of the step cycle the obstacle would be released and whether lengthening or shortening of the stride would be the most favorable response.

The average OA latency of 122 ms also compared very well to the latencies that were found for changing trajectories of upper extremity movements. Brenner and Smeets (2003) found latencies of just over 100 ms for deviations of reaching movements towards high contrast targets when the target was displaced during movement. Latencies were shown to increase with decreasing contrast. Day and Brown (2001) found average latencies of 137 ms in response to a target jump during reaching. Paulignan et al. (1991) found that the first adjustments in wrist trajectories during prehension movements occurred within 100 ms when the target was displaced. It was hypothesized that these reactions were fast, because they started from a dynamic situation. In contrast, in response to a target jump from a stationary starting position, the movement was supposed to be newly programmed. In case of a target jump during movement, the discrepancy between target position and limb position required automatic reorganisation of motor commands. This could explain the short latencies in dynamic situations during goal directed movements. The results of the present study confirm that the starting position might be an important determinant for latencies of OA reactions, as OA latencies were significantly faster as compared to those of SRT foot and hand. The SRT task required a response from a stationary starting position, while in the OA task the response was initiated from a dynamic situation. On the other hand, the OA latency was significantly shorter than the latency of voluntary stride modifications, while the starting position was the same in both tasks. Hence, the dynamic starting position cannot explain the short OA latencies. Instead, the nature of the cue and the context in which the cue was given presumably were important determinants for the short latencies of OA reactions.

Secondly, in the present study, no difference was observed between latencies of LSS and SSS reactions, neither during obstacle avoidance, nor during voluntary stride modifications. This indicated that both strategies had the same level of complexity. Previous studies have been conducted on the characteristics of stride length modifications (Var- raine et al., 2000; Bonnard and Pailhous, 1995), but the participants knew where and when they had to modify the walking pattern. In contrast, in the present study, unexpectedly required decrease or increase of stride lengths were used. From the study of Patla et al. (1991a) it was also unknown whether lengthening and shortening were equally fast, as only step lengthening was required. The observation that both LSS and SSS required the same amount of time to be implemented in the normal walking pattern is important with regards to obstacle avoidance behavior of elderly and patients. Obstacle avoidance strategies of elderly have been shown to be different from those of young adults (Chen et al., 1994a; Weerdesteyn et al., 2001). Chen et al. (1994a) found that at the same Available Response Time (ART) elderly used the SSS somewhat more as compared to young adults. In contrast, Weerdesteyn et al. (2001) showed that elderly had a strong preference for the LSS in order to avoid an unexpected obstacle. The latter results were in line with Den Otter et al. (2003), who studied obstacle avoidance strategies of stroke patients during treadmill walking. Stroke patients also had a strong preference for the LSS, whereas age matched controls showed similar behavior to the present group of young adults exhibiting both LSS and the SSS. It may be argued that the SSS possibly took more time to be executed and therefore was used less frequently. The results of the present study provide no indication that the SSS takes more time, as there was no significant difference in latencies between LSS and SSS reactions. However, the results of present study were obtained in young and healthy participants and may not be the same for elderly and stroke patients.

In addition to the result that there was no difference between latencies of LSS and SSS in response to an obstacle, participants who used both LSS and SSS were equally as fast as those who used either only LSS or SSS in order to avoid the obstacle. When both strategies were used by a participant, LSS and SSS were different from the start of the reaction (see Figure 2). This indicated that the OA reaction is not a primary stereotypical response that is later fine tuned into either LSS or SSS. Indirect evidence for this observation has previously been reported in the study of Patla et al. (1999) on selection of alternate foot placement with respect to a virtual obstacle. It was shown that for each configuration of the foot relative to the virtual obstacle there was a single dominant avoidance strategy. When time pressure increased for the same foot-obstacle configuration (shorter Available Response Time), this dominant strategy became even more dominant. This observation and the results of the present study show that the decision about the strategy to be chosen does not add to the time to make the visuo-motor transformation in obstacle avoidance.

The difference between the latencies of the four tasks and the finding that there was no significant correlation between OA latencies and the latencies of any of the other tasks are an indication that different pathways were involved in the different tasks. The question which pathway could be involved in obstacle avoidance is of particular interest, because the reactions were very fast. To our knowledge, no previous studies were reported in which possible pathways for this kind of lower limb reactions were investigated. For fast reactions during upper limb movements, a number of possible pathways have been described. For example, fast responses were shown to involve the parietal visual pathway (Pisella et al., 2000). Interestingly, Day and Brown (2001) provided evidence for the involvement of subcortical pathways in reaching adjustments. They studied a patient with complete agenesis of the corpus callosum, and a vestig-
ial or absent anterior commissure. As expected, during a simple reaction

time task, there was a significant difference between reaction times when

the stimuli were given contralateral as compared to ipsilateral stimuli. In

contrast, during reaching, trajectory adjustments in response to target

jumps to left and right produced similar and very short (120 ms) latencies.

This was a clear indication that subcortical pathways are involved in fast

reaching adjustments. So far, there is no direct evidence that subcortical

pathways play a role in obstacle avoidance reactions in humans, but their

possible involvement could be an interesting subject for further research.
INTRODUCTION

Falls in the elderly are a major health problem. Approximately 30% of community dwelling elderly over the age of 65 fall at least once a year and 6% of these falls result in fractures (Blake et al., 1988; Tinetti et al., 1988). In the past decade numerous studies have been conducted to investigate the effectiveness of fall preventive interventions. Exercise programs or multifaceted programs incorporating exercise training have been used in the majority of these studies. Although not all studies were equally successful in demonstrating the potential benefits of such exercise-based programs in the reduction of fall incidence in the elderly, recent meta-analyses of fall prevention programs have convincingly shown that exercise interventions are effective in reducing the risk of falls and fall injuries (Chang et al., 2004; Province et al., 1995; Robertson et al., 2002). However, the content of the optimal exercise program as well as its optimal duration and intensity have not yet been established. Most of the exercise programs that have been investigated were quite demanding to the participants, both with respect to duration, intensity and frequency. This demand resulted in high dropout rates and lack of compliance to the exercise regimen. Secondly, some of those programs that consist of large numbers of supervised exercise sessions may not be cost-effective and, thus, will be less suitable for implementation in daily clinical practice. From these perspectives, the development of a short-term low-intensity program was considered necessary, but the question whether such a program would be equally effective in the reduction of fall risk would still have to be answered.

In the development and evaluation of exercise-based fall prevention programs, there is another issue that deserves attention. It is still largely unknown which working mechanisms underlie the effectiveness of these programs. In previous studies, attempts have been made to answer this question. Many different assessments of balance, gait, muscle strength, and balance confidence have been used to evaluate the effects of the exercise programs in relation to their effects on fall incidence. The results, however, are not as straightforward as might be expected. For instance, in the Atlanta FICSIT trial, a balance-training program based on Tai Chi proved to be successful in reducing fall risk (Wolf et al., 1996; 1997). Sway amplitude, as a measure of postural stability obtained from force-plate posturography, however, did not show significant changes as a result of training. On the other hand, the study of Lord et al. (1995) showed significant improvements of total sway path as a result of training, but no overall reduction in fall incidents. These discrepancies suggest that the choice of posturographic parameters may influence the observed results.

The question emerges whether other functional tests would provide different information about the effectiveness of various exercise programs. One good candidate for such a test might be an obstacle avoidance task. It has been reported that in the population of community dwelling elderly over 50% of the falls are due to trips and slips, usually during walking (Berg et al., 1997). In many of these cases there is an external, provoking factor, like an obstacle that is tripped over (Tinetti et al., 1988). This fact possibly indicates that a decrease in the number of falls as a result of exercise programs would more likely be associated with improved functional walking skills, such as avoiding obstacles, than with ‘static’ balance.
tasks. Previously, an observation based obstacle course has been used to evaluate the effects of an exercise program, but it appeared not sufficiently sensitive to detect subtle changes over time (Means et al., 1996). In contrast, in an obstacle negotiation task with quantitative motion analysis, a number of parameters associated with safe obstacle negotiation improved as a result of strength training (Lamoureux et al., 2003). Hence, the benefits of such training could be demonstrated in the laboratory by using a functional walking task. This observation shows the potential usefulness of an obstacle avoidance task as an additional exercise program aimed at the prevention of falls. No previous studies have been conducted, however, to investigate whether improved performance of obstacle avoidance tasks in a movement laboratory is associated with a decreased fall risk.

The aim of the present study was to evaluate whether a new 5-week exercise program of low intensity, called the ‘Nijmegen falls prevention program’, would be effective in the reduction of the number of falls in community dwelling elderly people. Although this program is of low intensity, its content is rather unique, because balance and coordination are practiced, integrated in an obstacle course that simulates potential hazardous situations of daily life. These exercises also have to be performed while cognitive and motor dual tasks are imposed, as well as under visual constraints. In addition, the program incorporates exercises to simulate walking in a crowded environment and the practice of fall techniques. In order to gain insight into the potential underlying working mechanisms, posturographic assessments, subjective assessments of balance confidence and objective assessments of obstacle avoidance skills while walking on a treadmill were made before and after the exercise program.

METHODS

Participants and Study Design
Participants were recruited by means of newspaper advertisements. Participants had to be at least 65 years old and community dwelling. In addition, they should have experienced at least one fall in the year prior to participation and be able to walk 15 minutes without the use of a walking aid. The exclusion criteria were severe cardiac, pulmonary or musculoskeletal disorders, pathologies associated to increased fall risk (i.e. stroke or Parkinson’s disease), osteoporosis, and the use of psychotropic drugs. These criteria were checked by self-report. Table 1 includes some group characteristics at baseline. All subjects gave informed consent prior to participation. The study was approved by the local Medical Ethics Committee.

Of 183 applications for participation, 70 persons were excluded for various reasons, mostly because they had not experienced a fall or declined participation. Of the 113 participants that were included in the study, 49 fellers were randomly assigned to the exercise program (EX1). Of the other 64 participants, 6 persons dropped out before randomization for medical (n = 2) or social (n = 4) reasons. The remaining 58 participants were randomly assigned to the exercise program (EX2) (n = 30) or to the control group (CON) (n = 28). After randomization, the post-intervention posturographic and obstacle avoidance assessments could not be conducted for 1 participant in the EX2 group due to acute knee complaints (unrelated to the intervention) and for 2 participants in the CON group, 1 person due to intestinal complaints and 1 person refused the assessments. Figure 1 provides a detailed overview of the study’s chronology, also of the EX1 group.

<table>
<thead>
<tr>
<th>Table 1. Baseline group characteristics</th>
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<tbody>
<tr>
<td>EX1 group</td>
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<tr>
<td>-----------</td>
</tr>
<tr>
<td>Mean age (SD)</td>
</tr>
<tr>
<td>% female</td>
</tr>
<tr>
<td>Mean number of drugs (SD)</td>
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<tr>
<td>Falls: Fall incidence rate (falls/person year)</td>
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<tr>
<td>Number (%) of fallers</td>
</tr>
<tr>
<td>Quiet stance: RMS COP velocity in mm/s (SD)</td>
</tr>
<tr>
<td>Eyes open AP</td>
</tr>
<tr>
<td>Eyes open LAT</td>
</tr>
<tr>
<td>Eyes closed AP</td>
</tr>
<tr>
<td>Eyes closed LAT</td>
</tr>
<tr>
<td>Dual task AP</td>
</tr>
<tr>
<td>Dual task LAT</td>
</tr>
<tr>
<td>Compliant surface eyes open AP</td>
</tr>
<tr>
<td>Compliant surface eyes open LAT</td>
</tr>
<tr>
<td>Compliant surface eyes closed AP</td>
</tr>
<tr>
<td>Compliant surface eyes closed LAT</td>
</tr>
<tr>
<td>Weight shifting: Mean number of weight shifts (SD)</td>
</tr>
<tr>
<td>With visual feedback</td>
</tr>
<tr>
<td>Without visual feedback</td>
</tr>
<tr>
<td>Timed 1-leg stance (SD) number of seconds</td>
</tr>
<tr>
<td>Balance confidence ABC-score (SD)</td>
</tr>
<tr>
<td>Obstacle avoidance success rates (SD)</td>
</tr>
<tr>
<td>ART 200-250 ms</td>
</tr>
<tr>
<td>ART 250-300 ms</td>
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<tr>
<td>ART 300-350 ms</td>
</tr>
<tr>
<td>ART &gt; 350 ms</td>
</tr>
</tbody>
</table>

SD: Standard Deviation; AP: Anterior-Posterior direction; LAT: Lateral direction; ART: Available Response Time; *n = 30 for baseline fall measures; †Pre-last group difference between EX group and control group, P < 0.05; ABC: Activities specific Balance Confidence, range 0–100, higher scores indicate higher confidence.
A 5-WEEK EXERCISE PROGRAM CAN REDUCE FALLS AND IMPROVE OBSTACLE AVOIDANCE IN THE ELDERLY

Figure 1.
Flow chart outlining number of participants during the study

Procedure
After inclusion, a median baseline period of 6 months (mean 5.89 months, SD 2.21 months) started during which individual fall incidence was monitored. Thereafter, just before group assignment and randomization, a number of laboratory assessments of balance and obstacle avoidance took place. In addition, all participants received the Activities Specific Balance Confidence scale (ABC, Powell and Myers, 1995) to be completed at home. Within the following 4 weeks, those subjects assigned to the experimental intervention started the 5-week exercise program. The other (control) subjects did not receive any specific treatment. For all participants, the laboratory assessments and completion of the ABC were repeated within the 4 weeks following the exercise program or within 5-9 weeks from the moment of group assignment. Fall incidence was monitored during a 7-month follow-up period from the moment of group assignment.

Exercise Program
The 5-week exercise program consisted of 10 sessions (2 sessions per week) of 1.5 hours each. The first session of the week was dedicated to balance, gait, and co-ordination training in an obstacle course, which mimics activities of daily life with potential fall risk. Some examples of the elements in the obstacle course are walking over doorsteps, stepping stones, uneven pavement, and over various kinds of ground surface. Reaching from a stool, standing up from a low chair without use of the arms, and making a transfer from stance to a kneeling position were also components of the balance and co-ordination training. To simulate the complexity of daily life, the balance and gait tasks had to be performed simultaneously with various additional motor and cognitive tasks (25% and 20% of the time, respectively) and under visual constraints (15% of the time). Motor dual tasks were carrying a tray with empty cups, carrying grocery bags or an umbrella. As a concurrent cognitive task, for instance, a story was told that had to be reproduced as well as possible after the participants had finished the obstacle course. A visual constraint was, for example, carrying a tray in front of the abdomen taking away the sight of the feet. During all the exercises, that closely resembled activities of daily life, participants not only practiced difficult situations, but they also learned to recognize and cope with potentially hazardous situations.

The second session of the week consisted of 2 elements. The first element was formed by a number of walking exercises that simulated walking in a crowded environment with many changes in speed and direction. The second element was based on the practice of fall techniques, derived from martial arts, in forward, backward and lateral directions. The level of difficulty was gradually enhanced by increasing fall height (from sitting on the safety mat to stance height) and time pressure.

Fall Incidence
A fall was defined as an undesired contact of any body part other than the feet with the ground or a lower surface. Falls were monitored monthly using pre-addressed, reply-paid fall registration cards. In addition to the question whether a fall had occurred in the past month, participants were asked to provide a short description of (a) possible fall(s) and of the body part(s) that had hit the ground. This information was used to determine whether each of the reported falls truly met the definition of a fall. Participants were requested to return these cards at the start of a new month. When no fall registration card had been received after 2 weeks, a postcard was sent as a reminder.

Balance Tasks
Balance measurements were made with a dual-plate force platform. Each force plate was placed on 3 force transducers, recording the vertical ground reaction forces at a sample rate of 60 Hz. The position of the center of pressure (COP) was determined for each sample by digital moment-of-force calculations. The coordinates of COP position were low-pass filtered (Fourier filter) with a cut-off frequency of 6 Hz. Root Mean Square (RMS) values of COP amplitude and velocity were calculated in both anterior-posterior (AP) and lateral (LAT) directions. The RMS COP velocity was selected as the primary measure of postural stability in each direction of body sway, because it has been shown that this measure is more reliable than the RMS COP amplitude (Geurts et al., 1993; Lafond et al., 2004).

The participants stood barefoot on the force platform with the arms alongside the trunk and the feet against a fixed foot frame (heel-to-heel distance 8.4 cm, 9° external rotation of the feet from the sagittal midline). During quiet standing, they were asked to stand as still as possible on normal and compliant surface (4.5 cm foam), both with eyes open and with eyes closed, and when concurrently performing an arithmetic task (on normal surface only). Each of these quiet stance conditions was repeated 3 times. COP fluctuations during each trial were recorded for 20 seconds. The first 5 seconds were always discarded from the analysis to eliminate any undesired starting effects. For each condition, the median RMS value of the 3 trials was included in the statistical analysis for the AP and LAT directions separately.

In addition, a weight shifting task was included in the posturographic assessment, both with and without visual feedback of the COP (Dault et al., 2003). A computer screen was placed 1 m in front of the participant.
tests were used to assess

while standing on the platform. A yellow and a blue square (3 x 3 cm) were presented on the screen at 40% of the length of the base of support from the rear. The middle of each square was positioned at 15% of the stance width (i.e. the distance between the anterior borders of both distal tibiae) from the sagittal midline, which corresponded to approximately 65% weight bearing on each corresponding leg to reach the middle of the target. Real-time real-size visual COP feedback was provided by a black cursor on the screen. Participants were asked to move the cursor from one square to the other by means of weight shifts. A successful weight shift was indicated by changing colors of the squares. In the visual feedback condition, the cursor was visible during the whole duration of the recording, which was 45 seconds. In the no visual feedback condition, the cursor was visible for the first 15 seconds, after which the weight shifts had to be continued for 30 seconds without feedback of the COP. One practice trial for each condition was performed and the second trial was recorded. For both conditions, the number of successful weight shifts during the latter 30 seconds was included in the statistical analysis.

As a clinical balance test, timed one-leg stance was performed with the preferred leg. A maximum of 5 trials was allowed and the best score, with a maximum of 30 seconds, was included in the statistical analysis.

Balance Confidence
The ABC was selected as a measure of balance confidence. The Dutch version of the ABC was used. Items on which more than half of the participants scored more than 90% of balance confidence at baseline were discarded from the analysis to avoid ceiling effects. The mean score on all remaining items of the ABC was included in the statistical analysis.

Obstacle Avoidance Task
For the obstacle avoidance task, participants walked on a treadmill at a fixed velocity of 3 km/hr. This speed was selected, because it falls well within the range of natural walking velocities of both young and older elders (Perry, 1992). A bridge was placed over the front of the treadmill, to which an electromagnet was attached. A wooden obstacle (size 40 x 30 x 1.5 cm in length, width, and height, respectively) containing a piece of iron was held by the magnet and could be released by a trigger timed by the computer. The height of the obstacle exceeded only slightly the minimal toe clearance height during unobstructed gait (Chen et al., 1991; Chou et al., 1997), so adaptations of stride length were required in combination with minor vertical adaptations. After release, the obstacle always fell in front of the left foot. Two reflective markers (diameter 3 cm) were attached to the left heel and the hallux. A third marker was placed on top of the obstacle. Marker positions were recorded by a 6-camera 3-D motion analysis system (Primas) at a sample rate of 100 Hz. The whole experiment was recorded on videotape.

Before the experimental procedure was started, the participants had an opportunity to get accustomed to treadmill walking. In addition, 5 practice trials of obstacle avoidance were performed. During the experiment, marker position recordings were real-time processed. Heel strike moment and position were determined and were used to predict the normal landing position. Based on this information the exact moment on which the obstacle had to be dropped was determined by the computer. The obstacle was not released until a regular walking pattern had been achieved, defined as less than 50 ms difference in stride duration between 2 consecutive strides.

The obstacle was dropped at 1 of 6 different moments during the step cycle, distributed from mid stance to mid swing of the left leg. These moments were chosen to obtain a wide range of resultant Available Response Times (ARTs, Chen et al., 1994b). The level of difficulty of obstacle avoidance tasks was known to depend on the ART. Mid stance obstacle release corresponded to relatively long ARTs (approximately 450 ms) and easy trials, while mid swing obstacle release corresponded to short ARTs (approximately 200 ms) and, thus, difficult trials. Each step cycle condition was repeated 5 times, randomly distributed across a total of 30 trials (3 series of 10 trials). Participants walked at a fixed position on the treadmill, so that the most anterior position of the toes had a distance of approximately 10 cm to the obstacle prior to its release. Participants were instructed to always avoid the obstacle. Failures were defined as contact of the foot with the obstacle and were noted during the experiment. In case of doubt, the video recordings were used to judge whether a trial was successful or not. Afterwards, for each trial the resultant ART was calculated (see Weerdesteyn et al., 2003). The ART was defined as the time span between obstacle release and the moment that the hallux would cross the front of the obstacle when no avoidance reaction would occur. Trials were subdivided into ART categories of 200-250 ms, 250-300 ms, 300-350 ms, and more than 350 ms. For each participant, success rates were calculated for each ART category by dividing the number of successful trials by the total number of trials in that ART category.

Statistical Analysis
First, it was planned to determine whether there were any pre-test differences on any of the outcome measures between the groups (EX1, EX2, and CON) by means of one-way ANOVAs, with post-hoc Bonferroni corrections. When no differences would be present between the EX1 and EX2 groups, further analyses could be conducted with the results of these experimental groups combined versus the control group on an intention-to-treat basis.

Fall data were analyzed with respect to total number of falls and the number of fallers (participants with at least one fall). Falls Incidence Rates (IR) during baseline and follow-up periods were calculated by dividing the total number of falls by the total number of person years. To compare the fall incidence rates between groups or between periods of time, a fall Incidence Rate Ratio (IRR) was calculated. The same was done to compare the incidence of fallers.

Repeated measures MANOVAs were conducted to compare changes in balance confidence and balance and obstacle avoidance performance, with Time (all analyses), Condition (analysis of quiet stance and weight shifting) and ART (analysis of obstacle avoidance) as within subject factors and Group as a between subjects factor. The alpha levels were .05. Post-hoc paired t tests were used to assess which of the conditions or ART categories showed significant differences. Alpha levels of .05 were corrected for the number of post-hoc tests per analysis per group.
RESULTS

Baseline group characteristics and exercise sessions attendance

The 3 groups were comparable with respect to age, gender, drug use, posturographic assessment, timed one-leg stance, balance confidence scores and obstacle avoidance performance at baseline (see Table 1). Despite randomization, the proportion of fallers in the control group was significantly smaller than in the EX2 group (p = 0.04), but fall incidence rates showed no differences between the groups. There was no baseline group difference in falls monitoring time, so this could not explain the smaller proportion of fallers in the COI group. There were no significant differences between the EX1 and the EX2 group for either the proportion of fallers or the fall incidence rate. Hence, in the statistical analyses the results of both exercise groups were combined. The mean attendance rate to the exercise sessions was 87% for both groups. Of all participants, 51% attended the maximum number of 10 sessions.

Falls

During the baseline period, there was 1 participant with 12 falls in the exercise group and 1 subject with 8 falls in the control group. To avoid overweighting of these participants, only the first 6 falls per person per period were included in the analyses of the total numbers of falls. The calculated fall incidences are presented in Table 2. In the exercise group, the falls IR decreased from 1.77 falls per person per year during the baseline period to 0.95 falls per person per year during the follow-up period (falls IR 5.4, 95% CI 3.6 - 7.9). In the control group, the falls IR was 1.77 falls per person per year during the baseline period and 1.75 falls per person per year during the follow-up period (falls IR 9.9, 95% CI 5.6 - 1.72). Comparing the follow-up falls IR between the exercise group and the control group, the falls IR was 0.54 (95% CI 0.34 - 0.86). The proportion of fallers in the exercise group decreased from 58% during the baseline period to 40% during the follow-up period (fallers IRR 0.61, 95% CI 0.38 - 0.98), whereas the proportion of fallers in the control group (32%) did not change. Because the proportion of fallers in the exercise group was larger than in the control group during the baseline period, this reduction in the proportion of fallers did not result in a significant difference between exercise and control group during the follow-up period.

Table 2

Falls in the exercise and control groups

<table>
<thead>
<tr>
<th>Exercise group</th>
<th>Baseline</th>
<th>Follow-up</th>
<th>Incidence Rate Ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of falls</td>
<td>55</td>
<td>43</td>
<td></td>
</tr>
<tr>
<td>Observation time (person years)</td>
<td>31.1</td>
<td>45.4</td>
<td></td>
</tr>
<tr>
<td>Fall incidence rate (falls/person/year)</td>
<td>1.77</td>
<td>0.95*</td>
<td>0.54 (0.36 - 0.79)</td>
</tr>
<tr>
<td>Number (%) of fallers</td>
<td>35 (58)</td>
<td>31 (40)†</td>
<td>0.61 (0.38 - 0.98)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control group</th>
<th>Baseline</th>
<th>Follow-up</th>
<th>Incidence Rate Ratio (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of falls</td>
<td>21</td>
<td>29</td>
<td></td>
</tr>
<tr>
<td>Observation time (person years)</td>
<td>11.8</td>
<td>16.6</td>
<td></td>
</tr>
<tr>
<td>Fall incidence rate (falls/person/year)</td>
<td>1.77</td>
<td>1.75*</td>
<td>0.98 (0.56 - 1.72)</td>
</tr>
<tr>
<td>Number (%) of fallers</td>
<td>9 (32)</td>
<td>9 (32)†</td>
<td>0.71 (0.28 - 1.78)</td>
</tr>
</tbody>
</table>

* IRR exercise group compared to control group 0.54 (95% CI = 0.34 - 0.86)
† IRR exercise group compared to control group 1.26 (95% CI = 0.60 - 2.64)

Table 3

Mean Values (SDs) for Pre- and Post-test Balance and Balance Confidence Measures

<table>
<thead>
<tr>
<th>Pre-test</th>
<th>Post-test</th>
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</thead>
<tbody>
<tr>
<td>Quiet stance: RMS COP velocity in mm/s</td>
<td></td>
</tr>
<tr>
<td>Eyes open AP</td>
<td>11.48 (7.97)</td>
</tr>
<tr>
<td>Eyes open LAT</td>
<td>5.74 (2.56)</td>
</tr>
<tr>
<td>Eyes closed AP</td>
<td>22.35 (24.52)</td>
</tr>
<tr>
<td>Eyes closed LAT</td>
<td>8.68 (9.38)</td>
</tr>
<tr>
<td>Dual task AP</td>
<td>13.06 (9.29)</td>
</tr>
<tr>
<td>Dual task LAT</td>
<td>5.69 (2.57)</td>
</tr>
<tr>
<td>Compliant surface eyes open AP</td>
<td>22.74 (10.70)</td>
</tr>
<tr>
<td>Compliant surface eyes open LAT</td>
<td>11.50 (3.93)</td>
</tr>
<tr>
<td>Compliant surface eyes closed AP</td>
<td>52.10 (25.73)</td>
</tr>
<tr>
<td>Compliant surface eyes closed LAT</td>
<td>22.23 (9.36)</td>
</tr>
<tr>
<td>Weight shifts: Mean number of weight shifts</td>
<td></td>
</tr>
<tr>
<td>With visual feedback</td>
<td>11.76 (2.56)</td>
</tr>
<tr>
<td>Without visual feedback</td>
<td>6.82 (3.38)</td>
</tr>
<tr>
<td>Timed 1-leg stance in seconds</td>
<td>20.75 (9.75)</td>
</tr>
<tr>
<td>Balance confidence</td>
<td></td>
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<tr>
<td>ABC-score†</td>
<td>59.88 (18.6)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Control group (n=26)</th>
</tr>
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<tbody>
<tr>
<td>Quiet stance: RMS COP velocity in mm/s</td>
</tr>
<tr>
<td>Eyes open AP</td>
</tr>
<tr>
<td>Eyes open LAT</td>
</tr>
<tr>
<td>Eyes closed AP</td>
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<tr>
<td>Eyes closed LAT</td>
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<tr>
<td>Dual task AP</td>
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<tr>
<td>Dual task LAT</td>
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<tr>
<td>Compliant surface eyes open AP</td>
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<tr>
<td>Compliant surface eyes open LAT</td>
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<tr>
<td>Compliant surface eyes closed AP</td>
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<tr>
<td>Compliant surface eyes closed LAT</td>
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<tr>
<td>Weight shifting: Mean number of weight shifts</td>
</tr>
<tr>
<td>With visual feedback</td>
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<tr>
<td>Without visual feedback</td>
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<tr>
<td>Timed 1-leg stance in seconds</td>
</tr>
<tr>
<td>Balance confidence</td>
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<tr>
<td>ABC-score†</td>
</tr>
</tbody>
</table>

AP: Anterior-Posterior direction, LAT: Lateral direction
Post-hoc comparisons with pre-test: *P < .05, **P < .01, ***P < .001
† ABC: Activities-specific Balance Confidence, range 0-100, higher scores indicate higher confidence
Balance Tasks

Pre- and post-intervention balance data were available for 101 participants. Table 3 shows means and SDs of balance and balance confidence measures for the exercise and the control group. In this table, only the RMS COP velocities are presented but RMS COP amplitudes showed a similar pattern of results and significance. Analysis of the RMS COP velocities during quiet stance revealed a significant Time x Group interaction ($F(1,195) = 4.424, p < .038$), but no significant main effect of Time ($F(1,95) = .404, p = .527$). Post-hoc analyses showed that the exercise group showed no significant difference between pre- and post-intervention assessments, whereas the control group showed a 12% increase in the RMS COP velocity in the anterior-posterior direction while standing on the normal surface with eyes open condition as well as a 14% decrease in the RMS COP velocity in this direction while standing on the compliant surface with eyes closed. Analysis of the number of weight shifts yielded a significant main effect of Time ($F(1,98) = 13.623, p < .001$), but no significant Time x Group interaction ($F(1,98) = .300, p = .585$). The exercise group improved 8-15% on both weight-shifting tasks, whereas the control group only improved the number of weight shifts made with visual feedback by 15%. Analysis of timed one leg stance yielded a main effect of Time ($F(1,99) = 14.336, p < .001$), but no Time x Group interaction ($F(1,99) = .127, p = .722$) (see Table 3). Post-hoc analyses showed that both exercise and control groups showed 12-16% improvement at the second assessment.

Balance Confidence

Six participants did not complete the ABC questionnaire correctly or did not return it, so that pre- and post intervention ABC scores were available for 95 participants. Seven items were deleted based on baseline assessment. Analysis of balance confidence scores revealed a significant Time x Group interaction ($F(1,93) = 4.18, p = .044$). At the end of the program, balance confidence had improved by 6% in the exercise groups, whereas the control group showed an insignificant (2%) deterioration across time (see Table 3).

Obstacle Avoidance Task

Six participants were not capable to perform the obstacle avoidance task, so that obstacle avoidance data were available for 95 participants. Obstacle avoidance success rates are shown in Figure 2. There was a significant main effect of Time on obstacle avoidance success rates ($F(1,86) = 46.48, p < .001$), which indicated that both exercise and control groups showed improved obstacle avoidance performance 5-8 weeks after group assignment. However, a significant Time x Group interaction ($F(1,86) = 5.39, p = .023$) indicated that the exercise group showed larger improvements of obstacle avoidance success rates (on average 12%) than the control group (on average 6%) and a significant Time x ART x Group interaction ($F(3,84) = 3.52, p = .018$) indicated that this difference was dependent on ART. Post-hoc analysis showed that the larger improvement in the exercise group as compared to the control group could be attributed to the trials of the short (< 350 ms) ART categories.

DISCUSSION

In the present study, the effects of a 5-week, low-intensity exercise program on falls, standing balance, balance confidence, and obstacle avoidance performance were investigated. One of the reasons to aim for a short-term and low-intensity program was to have optimal compliance to the exercise regimen. Both the high attendance rate (87%) and the small number of dropouts during the training period indicate nearly maximal compliance. Although the duration was short and the intensity low, the program proved to be successful in reducing both the number of falls and the number of fallers. Furthermore, the reduction of 46% in the number of falls was large compared to previous studies (Barnett et al., 2003; Campbell et al., 1997; Day et al., 2002; Wolf et al., 1996; 1997). A limitation of this study was that no randomization procedure was applied to the participants in the EX1 group. There were no baseline differences, however, between the EX1 and the EX2 group. In addition, the reductions in the number of falls were 45 and 49% in the EX1 and EX2 group, respectively. Hence, it is unlikely that the direct assignment of the EX1 group to the exercise program has biased the final outcome of this study towards a more positive outcome.

The shortest exercise programs that have been successful in the reduction of falls in community-dwelling elderly involved 15 week training periods (Day et al., 2002; Wolf et al., 1996; 1997). One of the main differences between previous exercise programs and the Nijmegen falls prevention program that may explain the good outcome of this study is the type of the exercises. In many studies, balance, gait, and coordination have been practiced using isolated exercises. In contrast, in this study these physical qualities were practiced in an exercise environment that simulated complex situations of everyday life. In this way, participants also learned to
recognize potentially hazardous situations and adopt strategies to minimize the risk of falling. Hence, the fall preventive effect of the Nijmegen falls prevention program may not only rely on physical training effects, but also on cognitive and behavioral changes. Indeed, the potential benefits of falls prevention programs targeted at both physical and cognitive-behavioral changes have recently been shown by Clemson et al. (2004). They observed a 31% reduction in falls as a result of such an intervention. The results of the present study are in accordance with Clemson’s study, but in addition, it was possible to show that the intervention resulted in functional changes related to the skills of obstacle negotiation.

The results of the applied obstacle avoidance task showed that the exercise group substantially improved avoidance success rates, and that the improvements were larger than in the control group at the shorter ARTs (200-350 ms). It has been shown that the initial timing of obstacle avoidance reactions is very fast (on average 122 ms, Weerdesteyn et al., 2004), which limits the possible contribution of cognitive control to the initiation of such gait adjustments. Because there is evidence that the effects of exercise training are more likely to be found in the spatial avoidance characteristics (e.g. foot-obstacle clearance), which are known to be accessible by cognition (Patla et al., 1996b), improved cognitive control of gait (especially under time pressure) may underlie the reduced incidence of falls as a result of the applied training program.

In the present study, posturographic assessments of quiet stance and weight shifting were performed as well, because functional balance training was another important aspect of the Nijmegen falls prevention program. However, these instrumented assessments did not provide clear evidence of improved automatic or voluntary control of posture. Still, the exercise group demonstrated a small improvement in balance confidence, which may have been influenced by an expectation effect. Taken together, a decreased number of falls, increased balance confidence, but a lack of training effects on basic control mechanisms of standing balance are in accordance with the results of Wolf et al. (1997). Quiet stance posturography has been designed to evaluate basic equilibrium reactions. Compared to reference values obtained from healthy elderly without a history of falls (Nienhuis et al., 2001), the participants in the present study demonstrated RMS COP velocities well outside the normal confidence limits, which is indicative of impaired equilibrium reactions. Hence, the absence of training effects on these balance tasks cannot be explained by floor effects.

An explanation for the observed lack of improvement is that the automatic equilibrium reactions responsible for the control of quiet standing are not responsive to exercise training. Previous training studies have yielded conflicting results with regard to this issue (Barnett et al., 2003; Crilly et al., 1989; Lichtenstein et al., 1989; Liu-Ambrose et al., 2004; Lord et al., 1995; McMurdo et al., 1993; Wolf et al., 1997). Although there is no final answer to this question yet, quiet stance assessment may not be the most suitable evaluation method to determine the effects of falls prevention exercise programs in community-dwelling elderly.

In anticipation of this, in the present study, two weight-shifting tasks have been added to the posturographic task set. However, both the exercise and the control groups showed significant increases in the number of weight shifts without clear differential effects. Recently, dynamic balance tasks have been used to evaluate the effects of a computerized balance training program for institutionalized elderly women (Sihvonen et al., 2004). The exercise group showed larger improvements on dynamic balance than the control group. Yet, these results may have been due to test-specific learning, as training and testing conditions were quite similar. Hence, it is still unclear whether dynamic balance tasks really have additional value to the usually applied static balance assessments in the evaluation of exercise programs.

In conclusion, the ‘Nijmegen falls prevention program’ was very effective in reducing the incidence of falls in otherwise healthy elderly. Force-platform posturography did not provide evidence of improved automatic or voluntary control of posture as mechanisms underlying this result. In contrast, an instrumented obstacle avoidance task indicated that subjects improved their performance, which may be explained by improved cognitive control of stepping. Laboratory obstacle avoidance tests may, therefore, be better instruments to evaluate future fall prevention studies than posturographic balance assessments. Our next step is to determine precisely which characteristics of obstacle avoidance contributed to the improved success rates.
Chapter 6

AdvanCing age Prolongedly affects obstacLe avoidanCe skills in the elderly

Adapted from Weerdesteyn V, Nienhuis B, Duysens J. Advancing age progressively affects obstacle avoidance skills in the elderly. Conditionally accepted.
INTRODUCTION

The ability to avoid obstacles while walking is an important motor skill that allows safe locomotion over uneven terrain. When an obstacle is not noticed or is avoided inadequately, this can easily lead to a trip and, possibly, a fall. A deterioration of this motor skill may increase the risk of falling over obstacles. Older people have frequently been reported to have high fall rates. One out of 3 people over the age of 65 falls at least once a year (Blake et al., 1988; Tinetti et al., 1988). Most of these falls occur during walking (Berg et al., 1997) and falls are frequently related to tripping over obstacles (Tinetti et al., 1988). It has been proposed that an age related decline in the skill of obstacle avoidance could contribute to the increased fall rates of elderly (Begg and Sparrow, 2000; DiFabio et al., 2004; McFadyen and Prince, 2002). In previous research, differences between young and older adults have been studied, in order to gain insight into the possible contribution of various parameters of obstacle avoidance to the increased fall risk of elderly (Begg and Sparrow, 2000; DiFabio et al., 2004; McFadyen and Prince, 2002).

Most studies on this topic have used an experimental setup in which a fixed obstacle, placed in the travel path, had to be avoided. In such a setup, optimal avoidance of the obstacle within the ongoing walking movement can be achieved by adaptation of spatial and temporal step characteristics during both approach and avoidance phase. In the approach phase, elderly have been shown to start adaptation of step length and step time one step earlier than young adults (Chen et al., 1994a). In the avoidance phase, 3 spatial avoidance parameters have frequently been used to describe avoidance behavior. These are the distance from the toe to the front of the obstacle (toe distance), the vertical distance of the foot over the obstacle (foot clearance), and the distance of the heel to the back of the obstacle (heel distance). With respect to toe distance, one study reported that older adults placed their foot further away from the obstacle than young adults (Patla et al., 1996a), while in 2 other studies there was no significant difference between the age groups (Chen et al., 1991; Draganich and Kuo, 2004). Compared to young adults, foot clearance of elderly has been reported to be either smaller (Begg and Sparrow, 2000; McFadyen and Prince, 2002), larger (Patla et al., 1996a; Watanabe and Miyakawa, 1994), or not significantly different (Chen et al., 1991; Draganich and Kuo, 2004). Heel distance was reported to be smaller in older adults (Begg and Sparrow, 2000; Chen et al., 1991; McFadyen and Prince, 2002). Hence, in fixed obstacle avoidance, only heel distance is consistently different between young and older adults. Toe distance and foot clearance do not show consistent age related differences, possibly because avoiding fixed obstacles is not sufficiently challenging to elicit deficits in gait adaptation skills. The observation that both young and older adults hardly ever contacted the fixed obstacle (Chen et al., 1991; Hahn and Chou, 2004; McFadyen and Prince, 2002) is in agreement with this.

Obstacle avoidance on short notice has been shown to be more challenging, as a reduction in the time to react to the obstacle (available response time, ART) resulted in more frequent contact of the foot with the obstacle in both young and older adults (Chen et al., 1994b; Patla, 1997; Patla et al., 1998; Weerdesteyn et al., 2005). Elderly were shown to have
In obstacle avoidance on short notice, 3 possible determinants of success can be identified. First, short ARTs require quick reactions, so reaction times are important. So far, obstacle avoidance success rates have only been studied for young adults and were shown to be very short (around 120 ms, Patla et al., 1991a; Weerdesteyn et al., 2004). Compared to young people, reaction times of elderly are commonly known to be longer (e.g. Steimach et al., 1987), which could contribute to age related deterioration in obstacle avoidance success rates.

Secondly, the position of the foot relative to the obstacle determines the optimal avoidance strategy (long stride strategy or short stride strategy; LSS or SSS). In an LSS avoidance reaction, the obstacle is crossed by means of a lengthened crossing step. In an SSS avoidance reaction, the pre-crossing step is shortened and the obstacle is crossed in the next step. In young adults, the optimal strategy has been shown to depend on minimal displacement of the foot from its normal landing position (Moraes et al., 2004; Patla et al., 1999; Weerdesteyn et al., 2005). Obstacle avoidance strategies in time critical conditions have previously been compared between young and older age groups. The behavior of the young adults agreed very well with the proposed criterion of minimal displacement (Weerdesteyn et al., 2005), despite the differences in experimental procedure with the original study of Patla and co-workers (1999). Older adults, however, showed a high preference for the LSS and the minimal displacement criterion was not strictly followed. In another study, the elderly tended to use the SSS more frequently at shorter ARTs than young adults. However, the methods were quite different since positions of the obstacle were not varied relative to foot landing positions (Chen et al., 1994a). Hence, the optimal strategy, as based on the minimal displacement criterion, was the same for all trials.

Finally, the spatial execution of the avoidance stride is important. The stride has to be lengthened (in LSS reactions) or shortened (in SSS reactions) sufficiently and the foot has to be lifted sufficiently not to touch the obstacle. So far, only one study compared toe distances and heel distances between young and older adults for obstacle avoidance on short notice (Chen et al., 1994a). In LSS reactions, crossing step lengths were significantly smaller in older adults, which was reflected by non-significant reductions in toe and heel distances.

In summary, it is not clear yet which determinant is responsible for the lower obstacle avoidance success rates of elderly. The present study was undertaken to shed light on the potential role of each of the 3 identified determinants in age related differences in obstacle avoidance success rates. Secondly, to our knowledge, no previous study has been conducted to investigate whether age related differences with advancing age in the group of elderly. Hence, the second purpose of this study was to investigate, for those parameters that showed age related differences, whether advancing age progressively affected these parameters within the group of elderly.
the level of difficulty of the obstacle avoidance trials was varied. A mid stance obstacle release trial corresponded to a large ART and, consequently, a low level of difficulty. In contrast, a mid swing obstacle release trial corresponded to a small ART and a high level of difficulty. The participants were requested to avoid the approaching obstacle. Stepping aside from the obstacle with the left foot was not allowed. Contact of the left foot with the obstacle was noted as a failure. In case of doubt, the video recordings were used to judge whether a trial was successful or not.

Data sampling and analysis

After the experiment, for each obstacle avoidance trial, the resultant ART was calculated (see Weerdesteyn et al., 2005). The ART was defined as the time span between obstacle release and the moment that the hallux would cross the front of the obstacle when no avoidance reaction would occur (Figure 1b). Obstacle avoidance success rates were calculated for ART categories of 200-250 ms, 250-300 ms, 300-350 ms, and 350 ms and more. Success rates were calculated by dividing the number of successful trials by the total number of trials in each ART category. In order to explain differences in success rates between young and older adults, a number of parameters were determined next.

For each participant, latencies of avoidance reactions were measured for late stance and early swing obstacle release trials. The first reaction was defined as the moment at which the differentiated acceleration curve of the avoidance swing phase exceeded the mean ± 2 standard deviations of the control swing phases. The latency was the time span between this moment and the moment when the obstacle started to fall (Figure 1c, for detailed explanation, see Weerdesteyn et al., 2004). The mean latency was used in the statistical analyses. Secondly, for each participant, total proportions (combined successful and unsuccessful) of LSS and SSS were determined from the marker position recordings, as well as proportions of unsuccessful LSS and SSS. In approximately 1% of all trials, an intermediate avoidance strategy was observed, in which the ipsilateral step is shorted with foot placement in front of the obstacle (SSS initiation), but immediately followed by an ipsilateral step over the obstacle without a contralateral step in between. These trials were discarded from further analysis.

Finally, spatial parameters of successful avoidance strides were determined. For SSS avoidance reactions, these parameters were toe distance, foot clearance, and heel distance (Figure 1d). For LSS reactions, foot clearance and heel distance were determined. In the situation of an LSS, no foot placement in front of the obstacle occurs after obstacle release. Consequently, toe distance is not of interest to characterize spatial performance of LSS reactions. Because spatial parameters were supposed to be related to ART, the mean values of the spatial parameters were determined for each ART category separately. Hence, heel distances and foot clearances were determined for 2 strategies and 4 ART categories, while toe distances were determined for SSS reactions in 4 ART categories. Because the calculation was dependent on the observed behavior (LSS or SSS) and was only performed for successful trials, the number of categories with valid observations could differ between participants.

Figure 1. (a) Schematic diagram of the experimental setup. The electromagnet (dashed black) is attached to a bridge over the front of the treadmill. After the electromagnet has been switched off by a trigger from the computer, the obstacle falls onto the treadmill in front of the participant’s left (ipsilateral) foot. (b) The ART was determined by extrapolation of the trajectory of the marker on the hallux during the control step in the following step during which the obstacle appeared. The toe and obstacle positions are shown after transformation to overground walking. For comparison, the thin line indicates the actually followed trajectory of the marker during obstacle avoidance, while the bold line indicates the extrapolated trajectory of the marker. This extrapolated trajectory would have been followed if no obstacle had been present. The ART was the time span between the moment at which the obstacle started to fall and the moment at which the ‘extrapolated toe’ would have crossed the front of the obstacle. (c) Determination of obstacle avoidance latencies. The grey area represents the mean differentiated acceleration curve ± 2 standard deviations of the control swing phases. The black line corresponds to the avoidance swing phase. The arrow indicates the first observable reaction to the obstacle. The obstacle starts to fall at Time = 0 ms. (d) Definitions of toe distance, foot clearance, and heel distance. The black horizontal bar indicates the obstacle.

The arrow indicates the first observable reaction to the obstacle. The obstacle starts to fall at Time = 0 ms. (d) Definitions of toe distance, foot clearance, and heel distance. The black horizontal bar indicates the obstacle.

Figure 1b reprinted from Weerdesteyn V, Van Wezel BMH, Duysens J, Mechanically induced stumbling during human locomotion. J Mot Behav 35:53-63 © 2003 with permission of Heldref Publications.

Figure 1c reprinted from Weerdesteyn V, Van Wezel BMH, Duysens J, Distraction affects obstacle avoidance during walking. J Mot Behav 35:53-63 © 2003 with permission of Heldref Publications.

Figure 1d reprinted from Schillings AM, van Galen GP, and Duysens J, Distraction affects obstacle avoidance during walking. J Mot Behav 35:53-63 © 2003 with permission of Heldref Publications.
For the analysis, first, the performance of young and older adults was compared. For all parameters, ANOVAs were conducted with 5 age groups: the young adults and the older adults subdivided into 4 age groups, which were 65-69 (n = 26), 70-74 (n = 29), 75-79 (n = 28), and 80 years and older (n = 16). ART category was included as a covariate in the analyses of success rates and the spatial parameters. Post-hoc contrasts were determined to differentiate between the young and each of the older age groups. Secondly, linear regression analyses were conducted within the group of older adults in order to determine which parameters change with progressing age. In the analyses of success rates and spatial parameters, both age and ART were used as independent variables. In the analyses of latencies and proportions of LSS and SSS, age was the independent variable. An alpha level of 0.05 was used for all statistical analyses.

Table 1. Means and standard deviations of the obstacle avoidance parameters for both young and older adults.

<table>
<thead>
<tr>
<th></th>
<th>Young (n = 25)</th>
<th>Older (n = 99)</th>
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<tbody>
<tr>
<td><strong>Success rates (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ART 200-250 ms</td>
<td>86.1 (22.2)</td>
<td>54.1 (34.5)</td>
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<tr>
<td>ART 250-300 ms</td>
<td>95.9 (6.9)</td>
<td>67.3 (30.3)</td>
</tr>
<tr>
<td>ART 300-350 ms</td>
<td>99.6 (2.2)</td>
<td>78.4 (23.8)</td>
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<tr>
<td>ART &gt; 350 ms</td>
<td>99.3 (2.3)</td>
<td>93.4 (9.8)</td>
</tr>
<tr>
<td><strong>Reaction times (ms)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total LSS</td>
<td>122 (2.8)</td>
<td>148 (1.6)</td>
</tr>
<tr>
<td>Total SSS</td>
<td>44.0 (28.7)</td>
<td>72.9 (20.4)</td>
</tr>
<tr>
<td>Failed LSS</td>
<td>54.7 (28.1)</td>
<td>24.9 (19.2)</td>
</tr>
<tr>
<td>Failed SSS</td>
<td>1.5 (3.1)</td>
<td>12.8 (11.9)</td>
</tr>
<tr>
<td>Spatial characteristics (mm)</td>
<td></td>
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<tr>
<td>Overall LSS foot clearance</td>
<td>100.1 (30.0)</td>
<td>136.0 (57.3)</td>
</tr>
<tr>
<td>Overall LSS heel distance</td>
<td>82.9 (52.4)</td>
<td>45.6 (38.2)</td>
</tr>
<tr>
<td>Overall SSS foot clearance</td>
<td>171.3 (82.4)</td>
<td>96.5 (79.9)</td>
</tr>
<tr>
<td>Overall SSS heel distance</td>
<td>86.2 (54.5)</td>
<td>168.8 (61.2)</td>
</tr>
<tr>
<td><strong>Strategies (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total LSS</td>
<td>44.0 (28.7)</td>
<td>72.9 (20.4)</td>
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<td>Total SSS</td>
<td>54.7 (28.1)</td>
<td>24.9 (19.2)</td>
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<tr>
<td>Failed LSS</td>
<td>1.5 (3.1)</td>
<td>12.8 (11.9)</td>
</tr>
<tr>
<td>Failed SSS</td>
<td>3.8 (4.2)</td>
<td>10.0 (9.8)</td>
</tr>
</tbody>
</table>

**RESULTS**

Means and standard deviations of obstacle avoidance success rates and the 3 chosen determinants of success of young and older adults overall are shown in Table 1. In order to investigate whether the avoidance performance of young and older adults was different, success rates were compared first. Obstacle avoidance success rates of older adults were significantly smaller compared to young adults (main effect of Age, $F(4,480) = 23.204, p < .001$, see Figure 2). Obstacles are more difficult to be avoided when ART is short, which is shown by the significant main effect of ART ($F(4,480) = 137.082, p < .001$). With increasing ART, the differences between young and older adults became smaller (Age x ART interaction, $F(4,480) = 7.892, p < .001$). In the ART category of 200-250 ms, the differences were 32%, while there was only 6% difference in success rates when the ART was larger than 350 ms. The post-hoc contrasts revealed that the young adults were significantly more successful than the 3 oldest age groups (all $p$ values < .001). There was no significant difference between young adults and the 65-69 year olds ($p = .74$). Within the older age group, both ART and age were found to be significant predictors of obstacle avoidance success rates ($p < .001$, success rate ($\%$) = $-1.22\*Age + 1.17\*ART + 130.6$). Success rates decreased with progressing age and with decreasing ART.

Figure 2. Means and standard errors of success rates of the 5 different age groups for the 4 categories of available response time (ART).

To understand the reasons for the decline in success rate with age 3 types of factors related to obstacle avoidance were investigated. First the question was investigated whether increased failure rates could be due to increases in reaction times. There was a significant main effect of age on avoidance reaction times ($F(4,118) = 20.818, p < .001$). Compared to the young adults, the older age groups all had longer latencies of the avoidance reactions (post-hoc contrasts, all $p$ values < .001). Within the group of elderly, age was a significant predictor of avoidance reaction times ($p < .001$, latency (ms) = 1.16$\times$Age + 63.1, see Figure 3) and reaction times increased with progressing age. The mean latency of the avoidance reaction increased from 141 ms (SD 12 ms) in the group of 65-69 year olds to 159 ms (SD 20 ms) in the oldest age group.

The choice of an avoidance strategy was considered as the second possible determinant of success. Age had a significant main effect on proportions of total SSS (successful and unsuccessful, $F(4,119) = 10.634, p < .001$), and consequently, on proportions of total LSS ($F(4,119) = 8.923, p < .001$) (Figure 4). Compared to the young, all older age groups had smaller proportions of total SSS (post-hoc contrasts, all $p$ values < .001), and consequently, larger proportions of total LSS (all $p$ values < .001). The young adults closely approached the distribution predicted by the criteria.
of Patla et al. (1999) with an average proportion of 54.7 % SSS (SD 28.1 %). In contrast, the older adults had a very different distribution with an average proportion of 24.9 % SSS (SD 19.2 %). Age also had a significant main effect on proportions of unsuccessful SSS ($F(4,119) = 5.775, p < .001$) and on proportions of unsuccessful LSS ($F(4,119) = 10.697, p < .001$). Compared to the young, all older age groups had larger proportions of unsuccessful LSS (post-hoc contrasts, all $p$ values < .05). Proportions of unsuccessful SSS were smaller in the young age group compared to the 3 oldest age groups (all $p$ values < .01), but no significant difference was observed between the young adults and the 65-69 year olds ($p = .542$). When the proportions of unsuccessful SSS as a function of the total number of SSS reactions (instead of total number of trials) were compared between the young and the 65-69 year olds, the young were much more successful in the execution of the SSS (16.2 % vs. 46.4 %, respectively, $p = .004$). This larger SSS error rate of the 65-69 year olds compared to the young, however, could be partly explained by differences in ART. As a result of the age related difference in the distribution of avoidance strategies, the elderly performed their (small amounts of) SSS reactions predominantly in the most difficult trials (very short ART, 200-250 ms), whereas the young also show a considerable amount of SSS reactions in less difficult trials (ART of up to 400 ms).

Figure 3. Scatterplot of the individual reaction times of the older adults. The solid line represents the regression line. The dotted line indicates the mean reaction time of the young adults.

The proportions of unsuccessful LSS and SSS in older adults were on average 11.3 % and 6.3 % larger than in young adults ($p < .001$). Within the group of elderly, proportions of total LSS and SSS were not related to age, but the proportions of unsuccessful LSS and unsuccessful SSS were predicted by age ($p < .001$ and $p = .012$, respectively, unsuccessful LSS (\%) = .74*Age – 41.7, unsuccessful SSS (\%) = .44*Age – 22.5). Proportions of unsuccessful LSS and SSS increased with progressing age.

Finally, spatial characteristics of the avoidance reactions were analyzed. For the SSS, age had a significant main effect on toe distance ($F(4,228) = 3.429, p = .01$) (Figure 5), on foot clearance ($F(4,228) = 4.031, p = .004$), and on heel distance ($F(4,228) = 12.662, p < .001$). Compared to the young, SSS toe and heel distances were smaller in all older age groups (all $p$ values < .05). SSS foot clearance was larger in the elderly (except for the 80+ group) than in the young ($p$ values < .05). Within the older age group, both age and ART were significant predictors of SSS toe distance ($p < .001$, toe distance (mm) = -2.9*Age + .80*ART + 91.4), but not of SSS heel distance and SSS foot clearance. With progressing age and with decreasing ART, toe distances decreased.

Figure 4. Distribution of successful and unsuccessful Long Stride Strategies (LSS) and Short Stride Strategies (SSS) of the 5 different age groups.

Figure 5. Means and standard errors of SSS toe distances of the 5 different age groups for the 4 categories of available response time (ART).
For the LSS, age did not have a significant main effect on foot clearance ($F(4,347) = 0.716, p = .582$) and on heel distance ($F(4,347) = 1.502, p = .269$). Average LSS heel distance of young adults, however, was nearly twice as large as those in the older age group overall (see table 1), but standard deviations within the age groups were quite large. When the older adults, as one group, were compared to the young, age did have a main effect on LSS heel distance ($F(1,353) = 5.155, p = .024$). Within the group of elderly, ART, but not age, was a significant predictor of heel distance ($p < .001$, heel distance (mm) = $54^*\text{Age} + .16^*\text{ART} - 50.3$). Heel distance increased with increasing ART.

**DISCUSSION**

The aim of the present study was to investigate age-related differences in obstacle avoidance success rates. In addition, the role of 3 possible determinants of success, namely reaction times, obstacle avoidance strategies, and the spatial parameters of obstacle avoidance (toe distance, foot clearance, and heel distance) were investigated. Avoidance success rates were significantly different between young and older adults, especially at short ART. The finding that obstacle avoidance success rates were smaller in older adults was in agreement with previous studies (Chen et al., 1994b; Weerdesteyn et al., 2005). In the study of Chen and co-workers (1994b), however, elderly would have needed only 30 ms additional ART to achieve the same success rates as the young. In the present study, these differences were larger. The young achieved a success rate of 86% in the ART category of 200-250 ms, while the older adults still performed worse (78% success rate) in the category of 300-350 ms. One reason for this discrepancy could be that the elderly in the study of Chen and co-workers (1994b) represented an elite group, whereas in the present study, fall-prone elderly participated. However, this is not likely the only explanation. In a previous study on healthy non-falling women, who were recruited from elderly sports groups, similar large age related differences were obtained in the same experimental setup (Weerdesteyn et al., 2005). Hence, other factors, such as the difference in experimental setups between the present study and the study of Chen and co-workers (1994b), are more likely to explain the differences in success rates. Chen and co-workers (1994b), for instance, used a narrow virtual obstacle (3 cm), which required relatively small stride length modifications. In the present study a 40 cm wide physical obstacle was used, which required much larger stride length modifications in order to allow the subjects to avoid the obstacle successfully.

Age related differences were also present in each of the 3 determinants of success investigated. Older adults had longer reaction times, smaller proportions of SSS (combined successful and unsuccessful), smaller toe and heel distances, but larger toe clearances. So far, to our knowledge, no previous study that compared obstacle avoidance reaction times of young and older adults. Although the older adults were slower compared to the young, the avoidance reactions were still fast (mean of 148 ms) compared to lower extremity simple reaction times of young adults (mean 179 ms, see Weerdesteyn et al., 2004). Avoidance strategies of young and older adults showed a different distribution. In the present study, a fifty-fifty distribution of LSS and SSS was to be expected in young adults if the minimal displacement principle was followed. This was indeed found in the young adult group. In contrast, the elderly preferred the LSS in most trials. The observation that the older adults highly preferred the LSS confirms previous findings on the same experimental setup (Weerdesteyn et al., 2004). With respect to failed trials, elderly showed increased proportions of both unsuccessful LSS and SSS. This shows that the decreased success rates cannot be attributed to increased numbers of failures in just one strategy.

With respect to the spatial characteristics of obstacle avoidance, SSS foot clearances were significantly larger in older adults. Though this behavior seems spatially not efficient, it reduces the risk of contact of the foot with the obstacle. This behavior can be interpreted as a safety strategy of elderly in obstacle avoidance, as has been reported previously (Chen et al., 1991; Hahn and Chou, 2004). An alternative explanation could be that elderly simply are less able to achieve low clearances. A recent study (Van Hedel and Dietz, 2004) showed that elderly had increased difficulties in adapting foot clearance towards an optimal level. Hence, the increased foot clearances could also be interpreted as an indication that the elderly could not use the available sensory input (visual input of obstacle height and proprioceptive input of limb position) adequately. The SSS toe distance, SSS heel distance and LSS heel distance were all smaller in the elderly compared to the young. A smaller SSS toe distance means an increased risk of hitting the obstacle with the toes, so not only the quantity, but also the quality of the SSS reactions showed an age related decline. Age related reductions in heel distance have been reported previously (Begg and Sparrow, 2000; Chen et al., 1991; McFadyen and Prince, 2002). A smaller LSS heel distance will increase the risk of heel contact with the obstacle. In the present study, however, one has to take into account that the elderly had shorter stride length to begin with. Hence, the smaller LSS heel distances can perhaps be explained by the shorter normal stride lengths of the elderly. The obstacle had a fixed length of 40 cm, so the relative length of the obstacle with respect to the stride length was larger for the elderly and, consequently, required a proportionally larger stride length modification.

**Age subgroups of elderly**

The second aim of this study was to investigate whether the relevant parameters that showed differences between young and older adults, progressively deteriorated with advancing age. Interestingly, success rates of the youngest elderly (65-69 years) were not significantly different from those of young adults, while the 3 oldest age groups did show reduced success rates. This decrease of success rates with advancing age was confirmed by the regression analysis, in which age was a significant predictor of success rates. On the basis of this result, it could be expected that a similar decline with advancing age would also be present in the 3 determinants of success investigated. This was not completely the case, however, with respect to the distribution of avoidance strategies. The overall distribution of avoidance strategies was not dependent on age, so progressing age apparently did not affect the LSS preference that was found for the elderly as a group. The finding that the youngest group of elderly achieved success rates, similar to those of young adults, indicated
that success rates are not determined by strategy choice and/or that these 'young' elderly can compensate for age related changes in this choice. With advancing age, these compensation mechanisms probably deteriorated, as success rates progressively declined. The proportions of unsuccessful LSS and SSS both increased with advancing age, so failures in both strategies contributed to the progressing decline of success rates. In obstacle avoidance on short notice, increasing reactions times could also lead to decreasing success rates. Avoidance reaction times were shown to increase with advancing age. Reaction times, even for the youngest elderly, were well above the reaction times of the young (see Figure 3), but this was not reflected in reduced success rates in the group mentioned. The increased avoidance reaction times, however, were in line with the results for SSS toe distance, in which age was a significant predictor of SSS toe distance. An SSS reaction requires a quick deceleration of the leg during swing, in order to prepare for foot placement in front of the obstacle. When reaction times increase, less time is available to shorten the stride, and toe distances may decrease as a result. The youngest elderly did show this possible negative effect of increased reaction times on SSS toe distances (see figure 5). Increased reaction times probably have less effects on LSS spatial characteristics, because after the initial reaction, there is much more time for leg acceleration (compared to the time for leg deceleration in SSS reactions) to allow for foot placement behind the obstacle. Nevertheless, proportions of unsuccessful LSS did increase with advancing age.

Taken together, these results suggest that progressing age in elderly affects both LSS and SSS reactions, which become increasingly difficult to perform successfully. On the other hand, the youngest group of elderly (65-69 years) did not have significantly reduced success rates. Their results on the 3 determinants of success, however, differed compared to the young adults, but, apparently, they were able to compensate for these changes. The fact that even the youngest group of elderly showed sizeable differences with the young raises the question at what age one should start to look for deterioration in these 3 determinants of success investigated. Obstacle avoidance characteristics of 40-65 year olds could probably give more insight into the effects of age on these parameters. The finding that advancing age negatively affects a number of important avoidance parameters also suggests that in obstacle avoidance tasks, elderly of varying ages should probably not be treated as a homogenous group.

In conclusion, the results of the present study show that the performance of older adults was worse compared to young adults on nearly all parameters tested, which makes all of these parameter possible contributors to the increased fall risk of elderly. The next question is whether any of these parameters could be improved by an exercise program. For example, avoidance success rates have already been shown to improve as a result of the Nijmegen falls prevention program and these improvements coincided with decreased fall incidence rates (Weerdesteyn et al., submitted). In a future study, the effects of this exercise program on the presently described 3 determinants of success will be investigated in order to determine which one could be responsible for the increased success rates and could possibly be involved in the reduction of fall incidence rates.
CHAPTER 7

SPATIAL CHARACTERISTICS OF TIME-CRITICAL OBSTACLE AVOIDANCE CAN IMPROVE AS A RESULT OF A FALL PREVENTION EXERCISE PROGRAM FOR THE ELDERLY

Adapted from Weerdesteyn V, Nienhuis B, Duysens J. Spatial characteristics of time-critical obstacle avoidance can improve as a result of a fall prevention exercise program for the elderly. Submitted.
INTRODUCTION

In daily life, independent and safe locomotion requires the ability to continuously adjust the locomotor pattern in response to environmental demands. Avoiding obstacles in the travel path is a frequently studied example of this adaptive locomotion. The characteristics of obstacle avoidance have been shown to be negatively affected by various pathological conditions, including stroke (Den Otter et al., 2005; Said et al., 1999; 2001), cerebellar damage (Morton et al., 2004), traumatic brain injury (McFadyen et al., 2003), Down syndrome (Virji-Babul and Brown, 2004), and osteoarthritis of the knee (Pandya et al., 2005). However, not only pathologies, but also the normal ageing process was repeatedly shown to have detrimental effects on obstacle avoidance (Chen et al., 1994a; 1994b; Hahn and Chou, 2004; McFadyen and Prince, 2002; Weerdesteyn et al., 2005). This may contribute to the high fall rates of elderly, since many fall incidents are caused by tripping over obstacles (Tinetti et al., 1988).

Treatments or interventions for these groups are often aimed at improvements of walking abilities in daily life and the prevention of falls. However, only a few studies have investigated the effect of a treatment or intervention on the performance of obstacle avoidance, even though the importance of adequate obstacle avoidance for safe locomotion is widely accepted. Jaffe and co-workers (2004) reported improvements of stroke patients on the maximum size of obstacle they could clear after they had received six sessions of obstacle avoidance training. Two studies have used an observation-based obstacle course to evaluate the effects of an exercise program for community-dwelling (Means et al., 1996) or institutionalized elderly (De Carvalho Bastone and Filho, 2004). Significant improvements on the obstacle course were reported for the institutionalized elderly (De Carvalho Bastone and Filho, 2004). For the higher functional, community-dwelling elderly no effect could be demonstrated, probably because this evaluation tool was not sufficiently sensitive to detect subtle changes over time (Means et al., 1996). Recently, avoidance of fixed obstacles on a walkway with quantitative motion analysis was used to evaluate the effects of strength training in elderly (Lamoureux et al., 2003). A number of parameters associated with safe obstacle negotiation were found to improve as a result of training, such as foot clearance and the distance from the heel to the back of the obstacle (heel distance)(Lamoureux et al., 2003).

In fixed obstacle avoidance studies, however, people could see the obstacle during multiple steps prior to obstacle crossing and they hardly ever contacted the obstacle (Chen et al., 1994a; Hahn and Chou, 2004; McFadyen and Prince, 2002). A more challenging locomotor task is the avoidance of obstacles under time pressure. Typically, the available response time (ART) is manipulated in such experiments. Hardly any contacts of the foot with an obstacle occurred when the ART was more than 450 ms, but when the ART became smaller than 450 ms, the number of foot contacts gradually increased (Chen et al., 1994b; Patla et al., 1999; Weerdesteyn et al., 2005). The next question was whether effects of training could be observed in such time critical obstacle avoidance. A treadmill obstacle avoidance task under time pressure has recently been used to evaluate the effects of a fall prevention exercise program for community-
dwellling elderly (The ‘Nijmegen falls prevention program’, Weerdesteyn et al, submitted). Avoidance success rates improved as a result of training, especially at short ARTs (less than 350 ms), in conjunction with a reduction in the number of falls. The mechanism, by which the increased success rates were achieved, however, remained to be determined.

The aim of the present study was to investigate which obstacle avoidance parameter(s) improved as a result of the ‘Nijmegen falls prevention program’, and could explain the increased avoidance success. In obstacle avoidance on short notice, 3 possible determinants of success can be identified. These determinants are the reaction times, the distribution of avoidance strategies, and the spatial characteristics of the avoidance stride. Because time critical obstacle avoidance requires quick reactions, avoidance reaction times were determined. Secondarily, avoidance strategies were considered. The main criterion for the choice of an avoidance strategy has been shown to depend on minimal displacement of the foot from its normal landing position (Moraes et al., 2004; Patla et al., 1999; Weerdesteyn et al., 2005). Hence, the spatial efficiency of the avoidance stride depends on the chosen avoidance strategy (long stride strategy or short stride strategy, LSS or SSS) in relation to the foot-obstacle configuration at obstacle release. Finally, the spatial execution of the avoidance stride is important. The stride has to be lengthened or shortened sufficiently and the foot has to be lifted sufficiently not to touch the obstacle. The 3 spatial characteristics that were considered were the distance from the toe to the front of the obstacle (toe distance), the vertical distance of the foot over the obstacle (foot clearance), and the distance of the heel to the back of the obstacle (heel distance).

It has been shown that the initial timing of obstacle avoidance reactions and the concomitant strategy choice are very fast (on average 122 ms in young adults, Weerdesteyn et al., 2004), which limits the possible contribution of cognitive control to the initiation of such gait adjustments. In contrast, for spatial avoidance characteristics it has been shown that adjustments can be mediated by cognition (Patla et al., 1996b). Hence, the effects of training were expected to occur most likely with respect to the spatial characteristics of obstacle avoidance.

METHODS

Participants

The subjects of this study were participants of the Nijmegen falls prevention program. A total of 113 participants were included in the intervention study. They were community-dwelling elderly over the age of 65. They all had experienced at least one fall in the year prior to participation. They had to be capable to walk at least 15 minutes without the use of a walking aid. People were excluded if they suffered from neurologic disorders, severe cardio-pulmonal or musculoskeletal conditions, or osteoporosis. They all gave informed consent to participate. This study was approved by the local medical ethics committee.

After inclusion, a median baseline period of 6 months started during which individual fall incidence was monitored. Thereafter, just before group assignment and randomization, the laboratory assessment of obstacle avoidance took place. Within the following 4 weeks, those sub-

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cycle, equidistantly distributed from mid stance to mid swing. In this way, the level of difficulty of the obstacle avoidance trials was varied. The participants were requested to avoid the approaching obstacle. Stepping aside from the obstacle with the left foot was not allowed. Contact of the left foot with the obstacle was noted as a failure. In case of doubt, the video recordings were used to judge whether a trial was successful or not.

**Figure 1.**
(a) Schematic diagram of the experimental setup. The electromagnet (colored black) is attached to a bridge over the front of the treadmill. After the electromagnet has been switched off by a trigger from the computer, the obstacle falls onto the treadmill in front of the participant’s left (ipsilateral) foot. (b) Determination of obstacle avoidance latencies. The grey area represents the mean differentiated acceleration curve ± 2 standard deviations of the control swing phases. The black line corresponds to the avoidance swing phase. The arrow indicates the first observable reaction to the obstacle. The obstacle starts to fall at Time = 0 ms. (c) Definitions of toe distance, foot clearance, and heel distance. The black horizontal bar indicates the obstacle.

**Data sampling and analysis**

The avoidance reaction time was the first parameter of interest. The reaction to the obstacle was defined as the moment at which the differentiated acceleration curve of the avoidance swing phase exceeded the mean ± 2 standard deviations of the control swing phases (Figure 1a). The latency was the time span between this moment and the moment when the obstacle started to fall (for detailed explanation, see Weerdesteyn et al. [2004]). Because in previous research no difference was observed in reaction times of LSS and SSS reactions (Weerdesteyn et al., 2004), the mean reaction time was determined for the strategies combined.

The second possible determinant of success was the distribution of avoidance strategies. The experimental procedure of the present study was designed in such a way that, when the participants would follow the minimal displacement criterion (Patla et al., 1999), an approximate fifty-fifty distribution of strategies would be expected. Distributions of strategies were calculated for each participant. The total proportions (combined successful and unsuccessful) of LSS and SSS were determined from the marker position recordings. In approximately 1% of all trials, an intermediate avoidance strategy was observed, in which the ipsilateral step was shortened with foot placement in front of the obstacle (SSS initiation), but immediately followed by an ipsilateral step over the obstacle without a contralateral step in between. These trials were discarded from further analysis.

Finally, the spatial outcome measures were calculated. For SSS avoidance reactions, spatial parameters were toe distance, foot clearance, and heel distance (Figure 1c). For LSS reactions, foot clearance and heel distance were determined. In the situation of an LSS, no foot placement in front of the obstacle occurs after obstacle release. Consequently, toe distance is not of interest to characterize spatial performance of LSS reactions. Because spatial parameters were related to ART, for each trial the resultant ART was calculated. Mean values of the spatial parameters of successful avoidance strides were determined for 4 categories of ART (200-250 ms, 250-300 ms, 300-350 ms, over 350 ms). Because the calculation was dependent on the observed behavior (LSS or SSS) and was only performed for successful trials, the number of categories with valid observations could differ between participants.

For the analyses, the pre- and post-test performances of exercise and control group were compared. For all parameters, repeated measures ANOVAs were conducted with time as a within-subjects factor and group as a between-subjects factor. ART category was included as a covariate in the analyses of the spatial parameters. An alpha level of 0.05 was used for all statistical analyses.

**RESULTS**

In the same group of participants, obstacle avoidance success rates of the exercise group showed larger improvements compared to the control group as a result of the Nijmegen falls prevention program (Weerdesteyn et al., submitted). In order to explain the larger increase of avoidance success rates of the exercise group, in the present study, 3 possible determinants of success were investigated. The first was the latency of the react-
tion in response to the approaching obstacle (Figure 2a). The repeated measures ANOVA yielded a small, but significant main effect of Time on avoidance reaction times ($F(1,92) = 0.925, p = .012$), but no Time x Group interaction ($F(1,92) = 0.255, p = .615$). Reaction times in the exercise group decreased from 148 ms (SD 16 ms) to 144 ms (SD 14 ms), whereas in the control group they decreased from 153 (SD 14 ms) to 148 ms (SD 13 ms).

The second parameter of interest was the choice of an avoidance strategy (Figure 2a). On the basis of the minimal displacement criterion (Patla et al., 1999), a fifty-fifty distribution of LSS and SSS reactions was expected if elderly would behave similar to young adults. At pre-test, however, neither exercise nor control group showed the expected fifty-fifty distribution. Both groups had a strong preference for the LSS. Analysis yielded no main effect of Time ($F(1,93) = 3.706, p = .057$) and no Time x Group interaction effect ($F(1,93) = 0.466, p = .496$) on the proportion of LSS and SSS reactions. The average proportions of SSS reactions in the exercise group were 22.9 % (SD 18.2 %) at pre-test and 19.0 % (SD 19.3 %) at post-test. The control group had SSS proportions of 34.3 % (SD 23.3 %) and 32.5 % (SD 24.5 %) at pre- and post-test, respectively. Hence, both groups maintained the same distribution of strategies at post-test.

DISCUSSION

In previous research, obstacle avoidance success rates were shown to improve as a result of an exercise program (Weerdesteyn et al., submitted). The aim of the present study was to investigate by which mechanism these improvements were achieved. Three possible determinants of success were investigated. The main finding was that the participants in the exercise group made larger steps across the obstacle, resulting in a longer heel distances, following the intervention. In both LSS and SSS reactions, the exercise group increased heel distance, while the control group did not. Increased heel distance results in reduced risk of heel contact with the obstacle and, consequently, larger avoidance success rates can be expected. In a previous study in which avoidance of a fixed obstacle was assessed, Lamoureux and co-workers (2003) also showed increased heel distance after obstacle crossing in elderly as a result of a strength training program. Hence, heel distance showed effects of training in obstacle avoidance tasks both with and without time pressure.

The finding that in both studies, the training effects were observed in the same spatial obstacle avoidance parameter, heel distance, is striking, considering the differences in exercise regimens in the present study and the study of Lamoureux and co-workers (2003). In contrast to the study of Lamoureux et al. (2003), in the present study, exercises targeted at improvement of muscle strength were not included. In addition, improvement of muscle strength as a secondary effect of balance and gait training is not likely because of the short duration and the low intensity of the Nijmegen falls prevention program. The program of Lamoureux and co-workers (2003), on the other hand, did not contain any balance and gait exercises, nor the practice of fall techniques, which were the elements of
the 'Nijmegen falls prevention program'. It may be concluded that both
exercise regimens have a similar beneficial effect on the physical ability to
take sufficiently long crossing steps to avoid heel contact with the obsta-
cle.

Another explanation could be that there is one general mechanism
underlying the similar results (increased heel distance) for the two differ-
ent interventions. Previous studies, for instance, have shown that anxiety
and divided attention affected kinematic obstacle avoidance characteris-
tics in both young and older adults (McKenzie et al., 2004; Schrodt et al.,
2004; Weerdesteyn et al., 2003). Increased confidence in physical abilities
could be one general effect of exercise. This increased confidence might
result in longer strides because it possibly reduces the perceived neces-
sity to regain a relatively safe double support phase (after a challenging
crossing swing phase) as soon as possible.

There was also a difference in the results for the spatial parameters
between the study of Lamoureux and co-workers (2003) and the present
study. They reported increased foot clearance after training, which was
not observed in the present study. The reason for this discrepancy might
be found in the different types of obstacles used. Lamoureux and co-
workers (2003) used obstacle heights of 10-30% of leg length. In the pres-
cent study, the height of the obstacle (1.5 cm, about 2% of leg length) only
slightly exceeded the minimum toe clearance during unobstructed gait
(Chen et al., 1994a; Chou et al., 1997). Hence, horizontal, rather than verti-
cal adaptations in the stride were required. In addition, foot clearances of
the participants at pre-test were already quite large. Mean LSS foot clear-
ance was 14.0 cm and mean SSS foot clearance was 16.8 cm, so an addi-
tional clearance margin was barely needed.

With respect to the other possible determinants of success no changes
were observed related to the intervention. The choice of avoidance strate-
gies did not change as a result of training. A preference for the LSS was
observed, as has been reported previously for a group of older females
and for stroke patients (Den Otter et al., 2005; Weerdesteyn et al., 2005).
Hence, in all of these studies, an LSS preference resulted in preference for
an avoidance behavior, in which fairly large amounts of stride lengthening
were required. In the most extreme LSS cases, the normal stride had to be
lengthened by as much as 50% in order to avoid the obstacle success-
fully. It is therefore perhaps not surprising that the participants did not fur-
ther increase the proportion of LSS over SSS. Rather they preferred to
increase the safety margin of the LSS by making larger strides (increased
heel distance).

The observation that training effects were absent in other parameters
than heel distance may be understood considering the events in the time
window between obstacle release and heel placement after obstacle
crossing. In this sample of older adults, the initial reaction and, presum-
ably, the choice of the avoidance strategy occurred at approximately 150
ms after obstacle release (see also Weerdesteyn et al., 2004). It is not like-
ly that training will have an effect on these short latency events. In con-
trast, the decision about heel placement (heel distance) occurred at a
much later point of time. Foot placement in front of the obstacle, which is
the event related to SSS toe distance, took place between 250 ms and
400 ms after obstacle release. Foot placement behind the obstacle, which
is related to heel distance, occurred at 650-1000 ms after obstacle release.

In LSS reactions. Hence, the time to modify toe distance is shorter com-
pared to the time to modify heel distance. On the other hand, the finding
that training effects can be observed in events occurring within the dura-
tion of one stride is very encouraging with respect to the possibility to
modulate the kinematics of a fall. In case of a fall, the time between a slip
and the moment when a body part strikes the ground is approximately 700
ms (Groenqvist et al., 2001), which is comparable to the time between
obstacle release and post-crossing heel strike in LSS reactions. Hence,
the practice of fall techniques may enable elderly to modify the fall kine-
matics to reduce impact forces. The type of fall techniques that would be
most suitable for elderly are still a matter of debate (DeGoede et al.,
2003). In the Nijmegen falls prevention program, the elderly successfully
practiced martial arts fall techniques. In young adults, these techniques
have been shown to reduce hip impact forces during sideways falls
(Sabick et al., 1999). While more research is needed to determine the pro-
tective value of these techniques for older people, the present data indi-
cate that some training programs enable elderly to modify spatial charac-
teristics of events occurring within the time span needed to reduce fall
impacts.
CHAPTER 8
MARTIAL ARTS FALL TECHNIQUES DECREASE THE IMPACT FORCES AT THE HIP DURING SIDEWAYS FALLING

Adapted from Groen B, Weerdesteyn V, Duysens J. Martial arts fall techniques decrease the impact forces at the hip during sideways falling. Submitted.
INTRODUCTION

Hip fracture is a serious consequence of falls in elderly people. About 90 percent of the hip fractures are caused by falls (Cumming and Klineberg, 1994). In particular falls to the side and those with impact on the hip have an increased risk for hip fractures. Interventions that reduce the fall severity of these more dangerous falls are expected to decrease the risk of fractures (Greenspan et al., 1994; Nevitt and Cummings, 1993).

Experimental fall studies have shown, that to avoid hip impact during a sideways fall, young subjects use their hands and rotate the trunk (Hsiao and Robinovitch, 1998). For elderly, using the hands is not without risk, as hand impact increases the risk for wrist fractures (Nevitt and Cummings, 1993). Relaxing the body during descent could reduce the impact velocity (van den Kroonenberg et al., 1996), but not the hip impact force (Sabick et al., 1999). In contrast, a martial arts (MA) fall technique has been shown to reduce the hip impact force (Sabick et al., 1999). However, the MA technique was compared to falling with the body tensed, and not with a natural way of falling. Therefore, it remains unclear what the potential benefits are, not only for young adults, but also for elderly, to learn this technique. Knowledge in this area is needed since MA fall techniques are being successfully used in programs to prevent falls in elderly (Weerdesteyn et al., submitted). Furthermore, the high impact force at the hand that is used to break the MA fall raised concerns (DeGoede et al., 2003). It was suggested that hand impact would play a role in the reduction of hip impact force (Sabick et al., 1999), however it has not been proven. Hence, experiments are needed to determine if hand impact is essential to reduce hip impact force.

According to simple impact models, hip impact force is determined by hip impact velocity, the effective mass of that part of the body that is moving prior to impact, and the overall stiffness of the soft tissue overlying the hip (van den Kroonenberg et al., 1995). The effective mass is dependent on trunk orientation at impact in such a way that the more vertical the trunk, the larger the effective mass. Hence, other factors that may play a role in the reduction of hip impact by the MA technique are impact velocity and trunk orientation.

The purpose of this study was to get insight into the mechanism by which MA fall techniques would reduce hip impact force during sideways falling. The hypothesis was that differences in hand impact, impact velocity, and trunk orientation would provide an explanation.

METHODS

Six experienced judokas participated (age: 24.2±3.8 years, weight: 65.8±19.6 kg, experience: 13.0±6.8 years) and signed informed consent prior to participation. The protocol was approved by the Ethical Board of the region Arnhem-Nijmegen.

Forces were measured with a force plate (Kistler) at 2400Hz. The 3D-positions of reflective markers were simultaneously registered with a 6-camera motion analysis system (Primas®) at 100Hz. Markers were placed on the left shoulder, wrist and greater trochanter (GT) and a marker frame with three markers was attached to the left femur.
Three different fall techniques were studied: the block with arm (Block) or control, the MA with arm (MA-a) and the MA no arm (MA-na) technique. The Block technique is based on a natural equilibrium reaction of elderly in which they use compensatory trunk movements and react with their arms by stretching into the direction of the impending fall (Allum et al., 2002). The subjects were instructed to fall sideways on the hip and to use the outstretched arm to block the fall (Figure 1a). The MA-a technique is derived from judo. The fall is changed into a rolling movement while the arm is used to break the fall (Figure 1b). The MA-na technique is similar to the MA-a technique, but the subjects were instructed to hold the left arm above the ground.

Figure 1. Stick figures of sideways falls using the control and martial arts technique (frontal view). (a) Block with arm or control technique. The subjects were instructed to fall sideways on the hip and to use the arm to block the fall. (b) Martial arts with arm technique. The fall is changed into a rolling movement while the arm is used to break the fall. Impact is indicated by a broken arrow (\(\vec{F}\)).

Data collection started with a reference measurement to define the position of the GT with respect to the marker frame. The position of the GT during the falls was calculated based on the position and orientation of the marker frame using the method described by Söderkvist and Wedin (1993). Then the GT marker was removed. The testing protocol was similar to that used by Sabick et al. (1999). The subjects were sitting on their knees next to the force plate with the left arm in front of them. After voluntary initiation of the fall, they got a vocal instruction which technique they had to perform. Two series of 15 falls were performed. One series consisted of 5 Block falls and 10 MA-a falls. In the other series the MA-a falls were replaced by MA-na falls. Falls were performed in random order within in each series. The series were also performed in random order.

The instant of impact was defined as the instant at which the vertical force first exceeded 10N. Impact force was defined as the peak force in vertical direction and normalized to body weight (BW). Velocity was computed by numerical differentiation of position data and low-pass filtered with a fourth order Butterworth filter with a cut-off frequency of 10 Hz. Impact velocity was defined as the vertical velocity of the GT just before impact. Trunk angle (\(\alpha\)) was defined by the angle between the line connecting the GT and shoulder marker and the vertical at hip impact, substracted by the angle in the reference measurement (Figure 2c).

Data were averaged for each subject and for each technique. Differences between the techniques were examined with a non-parametric analysis of variance for repeated measurements (Friedman). Post hoc, two-tailed Wilcoxon signed-ranks tests for matched pairs were used to detect directional effects. An exact \(p\) value <0.05 was considered statistically significant.

**RESULTS**

The largest mean impact forces and velocities and the most vertical trunk orientations were found for the Block falls (Figure 2). The Friedman test revealed a main effect of technique on impact force (\(Fr = 9.333; p = 0.006\)), impact velocity (\(Fr = 10.333; p = 0.002\)) and trunk angle (\(Fr = 8.333; p = 0.012\)). Post hoc comparisons showed that the MA-a and MA-na technique significantly (both \(p=0.031\)) reduced the impact force by 27.0 and 29.5\%, respectively. The impact velocity was significantly lower in both the MA-a (-0.17 m/s; \(p=0.031\)) and MA-na (-0.21 m/s; \(p=0.031\)) falls compared to the Block falls. Further, a significantly less vertical trunk orientation was found in the MA-a (7.0 degrees; \(p=0.031\)) but not for the MA-na falls (4.5 degrees; \(p = 0.063\)) compared to the Block falls. No significant differences between the MA-fall techniques were observed (\(p > 0.05\)).

**DISCUSSION**

The results showed that the MA-a and MA-na technique reduced the hip impact force in sideways falls from kneeling height by 27.5 and 30\%, respectively. Sabick et al. (1999) found a smaller reduction (12\%), but they used 'tensed falls' as controls. They suggested that hand impact would be responsible for this reduction. In contrast, our study showed that hand impact is not an essential element of the MA technique in the reduction of hip impact force since no significant differences were found between the MA techniques with or without arm involvement. Hand impact might have a protective value for the head and shoulder. However, this could not be tested in the present study.
In conjunction with decreased impact force, hip impact velocity was significantly reduced in the MA falls. In addition, the trunk orientation was less vertical in the MA falls than in the Block falls, but the difference was significant only for the MA-a falls. According to simple impact models (van den Kroonenberg et al., 1995), this would result in a lower effective mass and thereby reduce the impact force. Hence, the data supported the hypothesis that hip impact velocity and trunk orientation would play a role in the reduction in hip impact force. It appears that in MA falls the normal equilibrium reaction is suppressed and hip velocity is changed into a more horizontal direction.

For safety reasons, the falls were performed from kneeling height. Although there are differences with falls from standing height, the principles of these MA techniques do not differ. Therefore, we believe that despite differences, the knowledge of the underlying mechanism is also applicable to falls from standing height. Whether such techniques can be used to reduce hip impact force in falls in the elderly remains a question for further research, preferably involving elderly. Experiences with these techniques within the ‘Nijmegen falls prevention program’ (Weerdesteyn et al., submitted) were promising. Elderly could learn these techniques within 5 training sessions and some participants reported that they had used these techniques in falls in daily life.

In summary, the MA fall techniques reduced the hip impact force by more than 25%, which was associated with a lower impact velocity and less vertical trunk orientation. Hand impact was not an essential element of the MA technique in the reduction of hip impact force. These findings provided support for the use of MA-na fall techniques in fall prevention programs for elderly.
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SUMMARY

CHAPTER 1.
GENERAL INTRODUCTION

The problem of falls in the elderly has become a topic of growing scientific interest. Numerous studies on risk factors for falls and preventive strategies have been published in the past decades. The development of fall prevention interventions has usually been based on these known risk factors. Another approach would be to develop an intervention program that is mainly based on the reported circumstances of falls. Such interventions would typically include elements like obstacle course walking, because a large number of falls in the elderly are a consequence of tripping and stumbling over obstacles while walking. The first aim of this thesis was to evaluate the effectiveness of a new falls prevention exercise program for the elderly, which was called the 'Nijmegen falls prevention program'. This exercise program was developed from the perspective of training in an exercise environment that simulated the most frequently reported circumstances of falls, such as obstacles that are encountered while walking. In order to enhance the probability of success of such intervention programs, it may help to get a better understanding of why elderly fall over obstacles. The second aim of this thesis was to provide more knowledge about the characteristics of obstacle avoidance under time pressure and about the influence of divided attention and aging on this task. Finally, the ultimate goal of the prevention of falls is the prevention of fall injuries. The third aim of this thesis was to explore whether the practice of martial arts fall techniques could potentially contribute to the prevention of fall injuries in the elderly.

CHAPTER 2.
DISTRACTION AFFECTS THE PERFORMANCE OF OBSTACLE AVOIDANCE DURING WALKING

In this chapter, a study was described in which dual task interference was examined in an obstacle avoidance task during human walking. Ten healthy young adults participated in the experiment. While they were walking on a treadmill, an obstacle suddenly fell on the treadmill in front of their left leg during either mid swing, early stance, or late stance of the ipsilateral leg. Subjects were instructed to avoid the obstacle, both as a single task and while they were concurrently performing a cognitive secondary task (dual task). Rates of failure, avoidance strategy, and a number of kinematic parameters were studied under both task conditions. Rates of failure on the avoidance task were larger during the dual task as compared to the single task in the condition with short available response times. Smaller crossing swing velocities were found during the dual task as compared to the single task. The difference in the crossing swing velocity can be attributed to increased stiffness of the crossing swing limb. The results of the present study indicate that in young and healthy subjects, divided attention affects obstacle avoidance performance during walking.
CHAPTER 5.
OLDER WOMEN STRONGLY PREFER STRIDE LENGTHENING TO SHORTENING IN AVOIDING OBSTACLES

This chapter describes a study on obstacle avoidance strategies during treadmill walking in 10 young (aged 19 to 32) and 10 older females (aged 65 to 78). Minimal displacement of the foot from its original landing position has been proposed to be the main criterion for the selection of alternative foot placement. Each participant performed 60 obstacle avoidance trials. Foot-obstacle configurations were varied in order to obtain both lengthening and shortening avoidance reactions. For each trial it was calculated how much lengthening and how much shortening of the stride was required minimally for successful avoidance. The difference between required lengthening and required shortening was expressed as a percentage of the control stride length and was used as a measure of minimal displacement. The behavior of young females was in agreement with the minimal displacement criterion. The older females, however, exhibited a strong preference for stride lengthening, even in situations in which stride shortening would be highly favorable. The explanation of the Long Step Strategy preference of the older females is discussed in terms of age-related changes in decision-making, in the unobstructed gait pattern and with respect to safety considerations.

CHAPTER 4.
GAIT ADJUSTMENTS IN RESPONSE TO AN OBSTACLE ARE FASTER THAN VOLUNTARY REACTIONS

It has been reported that obstacle avoidance reactions during gait have very short latencies. This raises the question whether the cortex can be involved, as it is in voluntary reactions. In this study, latencies of obstacle avoidance (OA) reactions were determined and related to latencies of voluntary stride modifications and simple reaction times (SRT) of hand and foot. Twenty-five healthy young adults participated in this study. While they were walking on the treadmill, an obstacle suddenly fell in front of their left leg. The first reaction to the obstacle was the moment at which the differentiated acceleration curve of the foot deviated from the control signal. Latencies of OA reactions were 122 ms (SD 14 ms) on average. Two very different avoidance reactions (lengthening and shortening of the stride) were noticed, but there was no avoidance strategy effect on OA latencies. OA latencies were significantly shorter as compared to latencies of voluntary stride modifications and simple reaction times of hand and foot. The short OA latencies could not only be explained from the dynamic nature of the task. It is suggested that subcortical pathways might be involved in obstacle avoidance.

CHAPTER 5.
A 5-WEEK EXERCISE PROGRAM CAN REDUCE FALLS AND IMPROVE OBSTACLE AVOIDANCE IN THE ELDERLY

The evaluation of the effectiveness of ‘the Nijmegen falls prevention program’ (a 5-week program, consisting of exercises on a functionally orientated obstacle course, walking exercises, and practice of fall techniques) in community-dwelling elderly people is presented in this chapter. Participants were 113 community-dwelling elderly, aged 65 to 88. The primary outcome measure was falls, monitored by means of fall registration cards. Secondary outcome measures were standing balance and obstacle avoidance performance, and balance confidence scores. The number of falls in the exercise group decreased by 46% compared to the number of falls during the baseline period and by 46% compared to the control group. Obstacle avoidance performance improved significantly more in the exercise group compared to the control group. Quiet stance and weight shifting measures did not show significant effects of exercise. In conclusion, the Nijmegen falls prevention program was very effective in reducing the occurrence of falls. There was no evidence of improved control of posture as a mechanism underlying this result. In contrast, an obstacle avoidance task indicated that subjects in the exercise group improved their performance.

CHAPTER 6.
ADVANCING AGE PROGRESSIVELY AFFECTS OBSTACLE AVOIDANCE SKILLS IN THE ELDERLY

The ability to adequately avoid obstacles while walking is an important skill that allows safe locomotion over uneven terrain. The high proportion of falls in the elderly that is associated to tripping over obstacles potentially illustrates an age-related deterioration of this locomotor skill. Some studies have compared young and old adults, but very little is known about the changes occurring within different age groups of elderly. In this study, obstacle avoidance performance was studied in 25 young (20-37 years) and 99 older adults (65-88 years). The participants walked on a treadmill at a speed of 3 km/h. An obstacle was dropped 30 times in front of the left foot at various phases in the step cycle. Success rates (successful avoidance) were calculated and related to the time available between obstacle appearance and the estimated instant of foot contact with the obstacle (Available Response Times or ART, ranging from 200 to more than 350 ms). In addition, latencies of avoidance reactions, the choice of avoidance strategies (long or short step strategy, LSS or SSS), and 3 spatial parameters related to the obstacle avoidance (toe distance, foot clearance and heel distance) were determined for each participant. Compared to the young, the older adults had lower success rates, especially at short ART. Furthermore, they had longer reaction times, more LSS reactions, smaller toe and heel distances, and larger foot clearances. Within the group of elderly, only the 65-69 year olds were not different from young adults with respect to success rate, despite clear changes in the other parameters measured. In particular, even this younger group of elderly showed a dramatic reduction in the amount of SSS trials when compared to young adults. Overall, age was a significant predictor of success rates, reaction times, and toe distances. These parameters deteriorated with advancing age. An exercise program has been shown to improve avoidance success rates, but the effects on the determinants of success still need to be assessed.
CHAPTER 7.
SPATIAL CHARACTERISTICS OF TIME-CRITICAL OBSTACLE AVOIDANCE CAN IMPROVE AS A RESULT OF A FALL PREVENTION EXERCISE PROGRAM FOR THE ELDERLY

Fall prevention programs have rarely been evaluated by quantitative movement analysis methods. Quantitative movement analyses could provide insight into the mechanisms underlying the effects of training. A treadmill obstacle avoidance task under time pressure has recently been used to evaluate the effects of a fall prevention exercise program for community-dwelling elderly. Avoidance success rates improved as a result of training. The mechanism, by which the increased success rates were achieved, however, remained to be determined. Participants were elderly who had fallen at least once in the year prior to participation. The 5-week exercise program consisted of exercises on a functionally oriented obstacle course, walking exercises, and practice of fall techniques. Pre- and post-intervention laboratory obstacle avoidance tests were conducted. Three possible determinants of success were investigated, namely avoidance reaction times, the distribution of avoidance strategies, and 3 spatial parameters (toe distance, foot clearance and heel distance). Analysis yielded significant Time x Group interactions in heel distances. The exercise group increased heel distance, while the control group did not. Increased heel distance may result in reduced risk of heel contact with the obstacle and, consequently, larger success rates. The remaining parameters showed no effect of training. In conclusion, the training program was effective in improving time-critical obstacle avoidance skills. In every day life, these effects of training may contribute to less obstacle-related fall incidents in elderly. In addition, these findings could indicate that the execution of other time-critical events, like an actual fall, could also be enhanced by training.

CHAPTER 8.
MARTIAL ARTS FALL TECHNIQUES DECREASE THE IMPACT FORCES AT THE HIP DURING SIDEWAYS FALLING

Falls to the side and those with impact on the hip are risky for hip fractures in elderly. Martial arts (MA) fall techniques can reduce hip impact force, but the underlying mechanism is unknown. Furthermore, the high impact forces at the hand used to break the fall raises concerns because of the risk for wrist fractures. The purpose of the study was to get insight into the mechanisms by which MA techniques reduce hip impact force. The hypothesis was that differences in hand impact, impact velocity, and trunk orientation would provide an explanation. Six experienced judokas performed sideways falls from kneeling height using three fall techniques: block with arm technique (control), MA technique with use of the arm to break the fall (MA-a), and MA technique without use of the arm (MA-na). The results showed that the MA-a and MA-na technique reduced the impact force by 27.5 and 30%, respectively. Impact velocity was significantly reduced in the MA falls. Trunk orientation was significantly less vertical in the MA-a falls. No significant differences were found between the MA techniques. It was concluded that the reduction in hip impact force was associated with a lower impact velocity and less vertical trunk orientation. Using the arm to break the fall was not essential for the MA technique to reduce hip impact force. These findings provided support for the incorporation of MA fall techniques in fall prevention programs for elderly. Since arm use was not beneficial it is proposed to preferentially use MA-na techniques.
SAMENVATTING

HOOFDSTUK 1.
ALGEMENE INLEIDING

Voor het probleem van het vallen bij ouderen bestaat een groeiende wetenschappelijke belangstelling. In de afgelopen decennia zijn talrijke studies naar de risicofactoren voor vallen en mogelijke preventiestrategieën gepubliceerd. Bij de ontwikkeling van valpreventie interventies heeft men zich meestal gebaseerd op deze bekende risicofactoren. Een andere aanpak zou kunnen zijn om een programma te ontwikkelen dat gebaseerd is op de gerapporteerde omstandigheden van valincidenten. In dit soort interventies zouden elementen opgenomen worden als het lopen over een obstakel parcours, omdat een groot aantal van de valincidenten bij ouderen het gevolg is van struikelen en vallen over obstakels tijdens het lopen. De eerste doelstelling van dit proefschrift was om het effect van een nieuw valpreventie oefenprogramma voor ouderen, genaamd ‘Vallen Verleden Tijd’, te evalueren. Dit oefenprogramma werd ontwikkeld met als uitgangspunt dat er getraind wordt in een oefensituatie waarin de meest gerapporteerde omstandigheden van valincidenten gesimuleerd worden, zoals obstakels die men tegenkomt tijdens het lopen. Het verkrijgen van meer inzicht in de redenen waarom ouderen vallen over obstakels zou de kans van slagen van dit soort programma’s kunnen vergroten. De tweede doelstelling van dit proefschrift was om meer kennis te verschaffen over de karakteristieken van het ontwijken van obstakels onder tijdsdruk en over de invloed van afleiding en van veroudering op deze taak. Tenslotte is het uiteindelijke doel van valpreventie het voorkomen van valgerelateerde verwondingen. De derde doelstelling van dit proefschrift was om te exploreren of het oefenen van valtechnieken uit de oosterse vechtsporten mogelijk zou kunnen bijdragen aan de preventie van valgerelateerde verwondingen bij ouderen.

HOOFDSTUK 2.
AFLEIDING BEÍNVLOEDT DE OBSTACLE ONTWIJKPRESTATIES TIJDENS HET LOPEN

In dit hoofdstuk wordt onderzocht hoe een dubbeltaak interfereert met het ontwijken van obstakels tijdens het lopen. Tien gezonde jongeren namen deel aan deze studie. Terwijl zij liepen op een loopband, viel plotseling een obstakel voor hun linker voet tijdens de mid-stand, late-stand of mid-zwaai fase van het linker been. De deelnemers waren geïnstrueerd het obstakel te ontwijken, zowel zonder (enkeltaak) als met een gelijktijdig uit te voeren cognitieve secundaire taak (dubbeltaak). Foutenpercentages, ontwijkstrategieën, en een aantal kinematische parameters werden onderzocht in beide condities. Wanneer er slechts weinig tijd beschikbaar was om op het obstakel te reageren was het percentage fouten in het ontwijken van de obstakels groter in de dubbeltaak- dan in de enkeltaaktconditie. Ook werd tijdens de dubbeltaak een lagere snelheid van het zwaaibeen tijdens het ontwijkstap waargenomen dan tijdens de enkeltaak. Het verschil in de snelheden van het zwaaibeen tussen beide taakcondities zou toegeschreven kunnen worden aan een verhoogde stijfheid van het zwaaibeen.
Deze resultaten gaven aan dat het afleiden van de aandacht de obstakel ontwikkelopstaties tijdens het lopen op een negatieve manier beïnvloedt bij jonge gezonde mensen.

HOOFDSTUK 3.
OUDERE VROUWEN HEBBEN EEN VOORKEUR VOOR SCHREDEVERPLELING BOVEN VERKORTING WANNEER ZIJ OBSTAKELS ONTWIKVEN.

In dit hoofdstuk is een studie beschreven naar de obstakel-ontwikkelstrategieën tijdens het lopen op een loopband bij tien jonge (19-32 jaar) en tien oudere vrouwen (65-78 jaar). Het minimaliseren van de verplaatsing van de voet ten opzichte van zijn originele landingsplaats werd verondersteld als het belangrijkste criterium voor de keuze van plaatsing van de voet. Iedere deelnemer ontweek het obstakel 60 keer. Voor ieder obstakel werd berekend hoeveel verlenging of verkorting van de schrede minimaal vereist was om het obstakel succesvol te ontwijken. Het verschil tussen vereiste verlenging en vereiste verkorting werd uitgedrukt als percentage van de normale schrede en werd gebruikt als maat voor de minimale voetverplaatsing. Het gedrag van de jonge vrouwen kwam overeen met het criterium van minimale voetverplaatsing. De oude vrouwen daarentegen lieten een grote voorkeur zien voor verlenging van de schrede, zelfs in situaties waarin verkorting van de schrede veel gunstiger zou zijn. De mogelijke veranderingen zijn bediscussieerd in termen van leeftijdsgerechte veranderingen in keuzeprocessen, verschillen tussen jong en oud in het normale looppatroon en veiligheidsoverwegingen.

HOOFDSTUK 4.
VERANDERINGEN IN HET LOOPPATOON IN RESPONS OP EEN OBSTAKEL ZIJN SNELLER DAN VRINJWILLIGE REACTIES.

Er is gerapporteerd dat obstakel-ontwikkelreacties tijdens het lopen korte latenties hebben. Dit werpt de vraag op of de cortex hierbij betrokken kan zijn, zoals bij vrijwillige reacties het geval is. In deze studie werden de latenties van obstakel-ontwikkelreacties bepaald en vergeleken met de latenties van vrijwillige modificaties in schredelengte en van enkelvoudige reactietijden van obstakel ontwijkreacties. De latenties van obstakel-ontwikkelreacties waren significant korter dan de van vrijwillige modificaties in schredelengte en van enkelvoudige reactietijden van hand en voet. De korte latenties van de obstakel-ontwikkelreacties konden niet worden verklaard uit de dynamische uitgangssituatie tijdens deze taak. Er wordt gesuggereerd dat subcorticale banen betrokken zouden kunnen zijn bij het ontwijken van obstakels.
HOOFDSTUK 8.

VALTECHNIEKEN UIT DE OOSTERSE VECHTSPORTEN REDUCEREN DE IMPACT KRACHT OP DE HEUP TIJDENS EEN VAL IN ZIJWAARTE RICHTING

Vallen in zijwaartse richting en valincidenten met impact op de heup le- veren een groot risico op voor heupfracturen bij ouderen. Valtechnieken uit de oosterse vechtsporten (OV) kunnen de impact kracht op de heup reduceren, maar het onderliggende werkingmechanisme is nog niet bekend. Ook bestond er bezorgdheid over de hoge impact krachten op de pols bij het afslaan in verband met het risico op polsfracturen. Het doel van deze studie was het werkingmechanisme achter de impactreductie van de OV valtechniek te achterhalen. De hypothese was dat dit verklaard zou kunnen worden uit verschillen in hand impact, snelheid bij impact en de oriëntatie van de romp bij impact. Zes ervaren judoka’s vielen vanaf kniehoogte op 3 verschillende manieren: het blokkeren van de val door de arm uit te steken (referentietechniek), een OV techniek met afslaan en een OV techniek zonder afslaan. De resultaten lieten zien dat bij de OV technieken met en zonder afslaan de impact kracht op de heup respectievelijk 27.5% en 30% lager was dan bij de referentietechniek. De snelheid bij impact was significant lager bij de OV technieken en de oriëntatie van de romp was minder verticaal bij de OV techniek met afslaan. Er waren geen significante verschillen tussen de beide OV technieken. De conclusie was dat de reductie in heup impact kracht geassocieerd was met een lagere impact snelheid en een minder verticale romporiëntatie. Het afslaan om de val te breken was geen essentieel onderdeel van de OV techniek om de impact op de heup te verminderen. Deze bevindingen ondersteunen het opnemen van OV valtraining in valpreventie programma’s voor ouderen. Omdat het afslaan geen toegevoegde waarde had voor de reductie van de impact kracht op de heup wordt de voorkeur gegeven aan het gebruik van OV technieken zonder afslaan.

SAMENVATTING

nen de groep ouderen vertoonde de groep van 65-69 jaar geen verschil in succes ratio’s ten opzichte van de jongeren, ondanks dat de andere gemeten parameters duidelijk verschillend waren. Vergeleken met de jongeren, vertoonde deze ‘jonge’ groep ouderen met name een drastische afname in het aantal korte stap strategieën. Binnen de groep ouderen was leeftijd een significante voorspeller van succes ratio, reactietijd en teenafstand. Deze parameters verslechterden met de leeftijd. Een oefenprogramma was succesvol gebleken in het verbeteren van de succes ratio’s, maar de effecten op de mogelijke determinanten van succes dienen nog nader te worden onderzocht.

HOOFDSTUK 7.

SPATIELE KARAKTERISTIEKEN VAN HET ONTIJKEN VAN OBSTAKELS ONDER TIJDSDRUK KUNNEN WORDEN VERBETERD MET EEN VALPREVENTIE OEFENPROGRAMMA VOOR OUDEREN

Valpreventie programma’s zijn zelden geëvalueerd met behulp van kwantitatieve bewegingsanalyse methodes. Kwantitatieve bewegingsanalyse methodes kunnen inzicht verschaffen in de werkingseigenheden van een bepaald training. Recentelijk is een tijdskritische obstakel ontwijkzaak op een loopband gebruikt ter evaluatie van de effecten van een valpreventie oefenprogramma voor zelfstandig wonende ouderen. Het percentage succesvol onweken obstakels (succes ratio) verbeterde als gevolg van de training. Het mechanisme op basis waarvan deze verbeterde succes ratio’s werden bereikt, diende echter nog bepaald te worden. De deelne- mers aan het oefenprogramma waren ouderen die minstens een maal gevallen waren in het jaar voorafgaand aan deelname. Het 5 weken durende oefenprogramma bestond uit een obstakel parcours, loopoe- feningen en het oefenen van valtechnieken. In het looplaboratorium werd zowel voor als na de interventie een obstakel ontwijkzaak verricht. Drie mogelijke determinanten van succes werden bestudeerd, namelijk de latentie van de ontwijkreactie, de distributie van ontwijkstrategieën en 3 spatiele parameters (tenenafstand, voelhoogte en hielaflstand ten opzichte van het obstakel). De analyses toonden een significante Meting x Groep interactie in de hakafstanden. In tegenstelling tot de controle groep, vertoonde de oefengroep grotere hakafstanden na de interventie. Een grotere hakafstand kan resulteren in een kleinere kans op hakcontact met het obstakel en, als gevolg daarvan, een grotere succes ratio. De overige parameters lieten geen effect van training zien. De conclusie was dat als gevolg van het oefenprogramma de obstakel ontwijkvaardigheden onder tijdsdruk verbeterden. In het dagelijks leven zouden deze trainingseffecten kunnen bijdragen aan een afname van het aantal obstakelgerelateerde valincidenten. Tevens zouden deze bevindingen een indicatie kunnen geven dat training ook de uitvoering van andere tijdkritische gebeurtenissen, zoals in het geval van een valincident, kan verbeteren.

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In hetzelfde jaar begon zij haar studie Biomedische Gezondheidswetenschappen (afstudeerrichting Bewegingswetenschappen) aan de Katholieke Universiteit Nijmegen. Tijdens haar afstudeerstage deed zij onder leiding van Prof. Dr. J. Duysens onderzoek naar de invloed van een cognitieve dubbelzaak op het ontwijken van obstakels. In 1999 studeerde zij cum laude af en haar afstudeervolgorad, getiteld ‘Distraction during Obstacle Avoidance Tasks in Young and Older Adults’ werd bekroond met de facultaire scriptieprijs 1999-2000. In afwachting van de start van haar promotie-onderzoek op 1 januari 2000 werkte zij part-time als fysiotherapeute in een particuliere praktijk in Oss en als biologiedocente aan het Rodenborch College te Rosmalen. Tijdens haar promotie-onderzoek op de Sint-Maartenskliniek te Nijmegen heeft zij, onder leiding van Prof. Dr. J. Duysens, de effectiviteit onderzocht van een nieuw ontwikkeld valpreventie-oefenprogramma voor ouderen, genaamd ‘Vallen Verleden Tijd’. Daarnaast heeft zij zich verder verdiept in de karakteristieken van het ontwijken van obstakels tijdens het lopen. Tenslotte kwamen haar judo-ervaringen goed van pas bij een eerste studie naar de impactreducerende effecten van de valtechnieken uit deze sport. De resultaten van het onderzoek staan beschreven in dit proefschrift.

Naast haar werk op de Sint-Maartenskliniek heeft Vivian haar part-time werk als fysiotherapeute tot op heden voortgezet. Sinds 2003 is zij tevens als docente betrokken bij de cursus ‘Valpreventie en valtraining’ van het Nederlands Paramedisch Instituut (NPI). In januari 2005 is zij gestart met een vervolgproject, waarin een aangepaste versie van ‘Vallen Verleden Tijd’ op effectiviteit wordt onderzocht bij osteoporosepatiënten.