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HEALTH & SAFETY LABORATORY

Trip Feasibility Study

Report Number
HSL/2006/77

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Executive Summary

A review of the literature showed that trips account for between 25 and 33% of all reported slip, trip and falls accidents each year, which corresponds to between 8000, and 12,000 accidents a year based on HSE RIDDOR statistics.

Research into the biomechanics of trips has shown that a trip results in a forwards fall with a frontal impact when no attempts at recovery are made. Three strategies for recovering from trips have been identified from the literature lowering, elevating and reaching.

Studies of induced trips have shown that there is a critical body orientation beyond which it is impossible to initiate a successful recovery attempt. The orientation of the body when a recovery attempt is made is dependent upon a number of factors including the walking speed prior to tripping and the reaction time, or time taken before the recovery attempt is made. It is therefore clear that either reducing the initial walking pace and / or improving the reaction time will improve the chances of executing a successful recovery.

Epidemiological studies of slip, trip and falls accidents have shown that the number of falls increases with age in both men and women, but that the increase is much more pronounced among women. This has traditionally been attributed to post menopausal changes reducing their ability to execute a successful recovery attempt and the onset of conditions such as osteoporosis increasing the likelihood of them sustaining a reportable injury. However these physiological changes alone are insufficient to account for the increase in slips, trips and falls among women.

There is evidence in the literature, which indicates that postmenopausal women may trip more frequently than their male counterparts, and it may be argued that a combination of physiological and “life-style” factors can be used to begin to explain the higher frequency of trips among women, but limited information is available in the literature in this area.

Studies have shown that forewarning of a trip hazard results in subjects significantly modifying their gait, with the toe clearance being increased by up to 50%.

The data available in the literature regarding toe clearance among the healthy population is severely limited, and there is a high degree of scatter among the little information available (0.87 – 2.19cm). A better understanding of how toe clearance varies with age and gender among the healthy population would be valuable in gaining a better understanding of trip accidents, and it is suggested that this is a suitable area for future research.

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Introduction

This work was carried out at the request of Mr. Stephen Taylor of the Construction Division Technology Unit.

Health and Safety Executive statistics show that pedestrian slip, tip and fall accidents are the most common cause of major injury in the UK workplace, and have accounted for over 34,000 injuries per annum since 1995 [HSE 2000/01, Thorpe et al 2002]. In the local authority enforced sector slips, trips and falls an a level (STF) accidents have been known to account for more than 42% of all major accidents and 23% of over 3-day injuries to employees [Hela 2001].

STF accidents are often more likely to be seen as humorous than serious and the consequences are assumed to be trivial. However analysis of medical records show that 48% of patients attending fracture clinics in the UK do so as a result of an injury sustained during an underfoot accident, and that up to half of these patients have considerable disability one year after injury [Davies et al. 2001], proving just how serious the issue of STF accidents is. It has been estimated that STF accidents cost the UK economy as whole in excess of £1 billion pounds per annum [Thorpe and Lemon 2000].

The number of STF accidents has remained approximately constant over the last ten years despite a range of initiatives undertaken to reduce the incidence of falls on a level. A substantial body of research has been carried out into the slip accidents, allowing minimum friction coefficients for the foot floor interaction to be established [Pye and Harrison] and the development of reliable measures for the quantification of slip risk to be developed [Thorpe and Lemon, Thorpe et al 2001]. The situation regarding the understanding of trip accidents is much less clear. This is an area where there are many accidents, but little is known about some of the causes and many questions remain to be answered:

- What are the key factors that lead to trips?
- What can be done about them?
- What are the effects of age?

The aims of this current review are:

- Review the available literature on trip accidents
- Identify key gait parameters related to tripping
- Gain a better understanding of the biomechanics of a trip during normal gait
- Evaluate the state of the art techniques currently used to study induced trips under laboratory conditions
- To recommend a suitable course of future research

Background Information

Defining a Trip

In epidemiological studies of slips, trips and falls on a level, a slip is generally associated with situations related to a loss of friction between the foot and the underfoot surface, and a fall generally refers to being brought to the ground [Lortie and Rizzo]. The concept of a trip is much less homogeneous; the definition perhaps most commonly encountered in the literature is that proposed by Manning who defined a *trip as the sudden arrest of movement of the foot with continued motion of the body* [Manning].

Trip Accident Statistics

A review of the available literature showed that numerous researchers have carried out detailed analyses of STF accident statistics from HSE, the Swedish ISA system, and private insurance company records. The aim of these studies was twofold, firstly to determine the accuracy of the classification systems used, and secondly to determine the ratio of the different types of fall. The event initiating a given fall accident was determined by a detailed examination of the accident descriptions.

These studies appear to indicate that the level of STF accidents is underestimated. The researchers found that greater weight was given to the cause of an injury, for example falling against machinery, than the initiating event, which may have been a slip or trip. Detailed examination of the accident descriptions let to a significant number of accidents being reclassified as STF incidents. The various studies showed that trips account for between 1 in 4 falls on a level [Lortie and Rizzo, Anderson and Lagerlöf, Dickerty] and 1 in 3 falls on a level [Lund, Cayless]. The assumption that trips account for between of 25% and 33% of STF accidents has been used to provide lower and upper bounds for estimating the number of trip accidents from the available HSE statistics, see Figure 1.

The initial analysis of the RIDDOR statistics indicates that trips probably account for between 8,000 and 12,000 reportable accidents each year. If the average reporting level of 44%, as estimated from the labour force survey, is taken into account, the estimated number of trip accidents rises to between 18,000 and 28,000 each year.

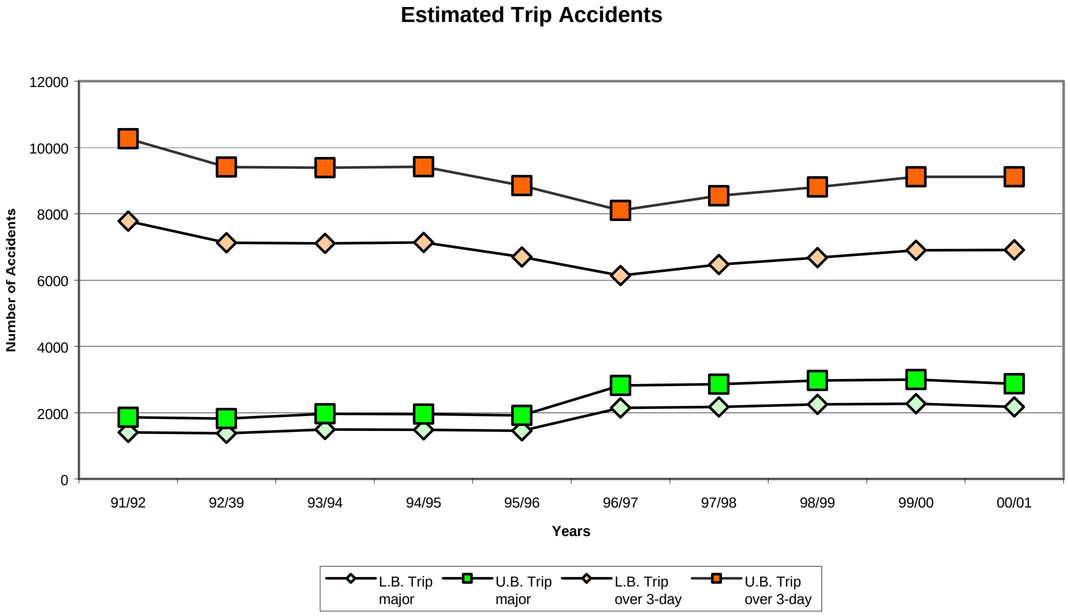

Figure 1 Graph showing the overall number of trip accidents as estimated from RIDDOR statistics. L.B. Trip major = the lower bound of trip related major accidents, U.B. Trip major = the upper bound of trip related major accidents. L.B. over 3-day = the lower bound for over 3-day accidents, U.B. over 3-day = the upper bound for over 3-day accidents

It is widely acknowledged that tripping accidents are a major cause of serious injury among elderly adults, accounting for up to 53% of all falls [Pavol et al. 1999b]. However researchers have discovered that individuals begin to have an increased relative risk of falls long before retirement age [McNamee et al, Anderson and Lagerlöf, Kemmlert and Lundholm 1998]. For example previous HSE studies have shown that the incidence of major occupational injuries due to falls rises sharply after the age of 45 in women but not in men. The women over 45 appeared to have a higher risk of falling even though they were not exposed to hazards different than the younger women [McNamee].

Types of Injury

Biomechanical studies of induced trips during normal gait have shown that when a person trips they always fall forwards [Smeeters et al., Winter]. If no attempt is made by the subject to save themselves, the trip results in a fontal abdominal impact [Smeeters et al.].

In reality it is likely that an individual who inadvertently tripped will make an attempt to recover himself or herself, at the very least it is likely that they would try and save themselves using their hands. The initial impact with the underfoot surface might therefore be expected to occur with the hands and forearms, which have relatively little protection to cushion them from impact compared to other parts of the body and are therefore susceptible to fracture of the wrist or collar bone. However previous reviews of HSE RIDDOR statistics have shown that the most likely sites of injury following a trip are the head, leg and then the wrist [Dickerty]. The discrepancies between the actual reported injury sites and those that might be predicted from the work of Smeeters is believed to be the result of the accident victims unsuccessful attempts to save themselves.

Studies of patients attending accident and emergency departments have shown underfoot accidents caused 75.9% of all fractures in women and 55.4% of all fractures in men [Davies et al.]. A random survey of fracture patients seen by surgeons found that 50% of patients had disability one year after injury. In addition to these serious injuries STF accidents also result in tens of thousands of “minor” injuries such as sprains, strains, contusions and lacerations each year [HSE].

The Biomechanics of Trips

The Current Literature

Numerous studies in to the biomechanics of induced trips during normal gait have been carries out over the previous decade. The aims of these studies have been many and varied:

- To determine the impact location following a trip
- The different recovery strategies used
- Effect of walking speed on trip outcome
- Effect of reaction time on trip out come
- Minimum toe clearances
- Effect of forewarning on gait patterns
- Effect of age on the risk of tripping

Likely Impact Location

Smeeters et al. investigated the fall direction and impact location for different types of induced fall (faint, slip, step down and trip) at three different gait speeds. The subjects involved in the trial were instructed to make no attempts to recover once their gait had been disturbed.

The researchers found that trips always resulted in a forwards fall with frontal impacts leading to abdominal pelvis impacts regardless of the gait speed of the subject when the trip was induced [Smeeters et al.].

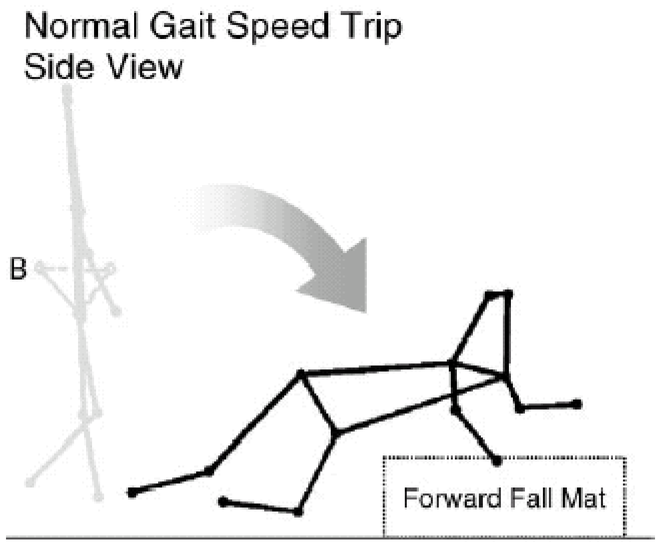

Figure 2 Side View of normal gait speed trip, approximate location of the forward fall mat also shown, after Smeeters et al..

These findings are line with the dynamic model for simulating trips that was developed by Zhou et al, which consistently predicted that the fall of the animated body would be to the front following tripping of the swing limb. It should be noted that in both of these studies no account was taken of the effect of unsuccessful recovery attempts on the fall direction and impact location. However it is intuitively sensible that an individual suffering and unrecoverable trip would fall forwards.

Researchers have also used an inverted pendulum model to simulate trip outcomes [Bogert et al.], where the subjects were modelled as a rigid body and it was assumed that after tripping the body would rotate around fixed axis represented by the stance foot ankle joint. Although simplistic this model allowed the effect of variables such as walking speed and response time on trip outcome to be investigated. As in the model developed by Zhou and the experiments conducted by Smeeters, this work also predicted that failure to recover from a trip would result in a fall forwards [Bogert et al.].

Different Strategies Used to Recover from Trips

Considerable research has been carried out with subjects to identify the different recovery strategies individuals employ when attempting to recover from induced trips, and to identify those which are most commonly and most successfully employed [Bogert et al, Owings et al, Pavol et al 2001, Eng et al.]. The following three common strategies for recovery have been identified:

1. Lowering strategy – In a lowering strategy the tripped foot is immediately lowered to the ground on the near side of the obstacle. The tripped limb then acts as the support limb as the collateral support limb executes the initial recovery step across the obstacle. This strategy is only observed in response to late swing perturbations.
2. Elevating strategy – In an elevating strategy the tripped limb is used as the recovery limb as the tripped foot is lifted over the obstacle in a continuation of the original step. The collateral stance limb acts as the support limb during the recovery step. Recovery limb flexion occurs at multiple joints. The strategy was predominately observed in response to early swing perturbations.
3. Reaching strategy – As in the elevating strategy the tripped limb is used as the recovery limb. Elevating and reaching strategies are differentiated by the fact that in a reaching strategy recovery limb flexion occurs primarily at the hip. This strategy is generally observed in response to late swing gait perturbations.

Independent of the strategy employed, successful recovery from a trip has been associated, conceptually with the ability to react rapidly [Bogert et al.] with an appropriate response to control the forward rotation of the trunk and execute a recovery step of sufficient length to establish a new functional base of support.

Effective use of the support limb to slow the fall of the head, arms, and torso during the stepping phase has also been shown to be important to the successfully recovery from a trip [Eng et al.]. Finally, successful recovery requires that the recovery limb provide sufficient hip height during stance for the support limb to execute an effective follow-through step.

Biomechanical studies of induced trips in mature adults showed a ratio of approximately 3:1 for the use of lowering and elevating recovery strategies, (though no attempt appears to have been made to differentiate between elevating and reaching recovery strategies.) [Pavol et al., 2001]. The recovery strategy used was significantly related to the phase of gait in which the trip occurred, with the odds of a lowering strategy being employed increasing by a factor of 1.31 for each 1% of stride length increase in the phase of gait.

Effect of Walking Speed on Trip Outcome

The evidence for the effect of walking speed on the outcome of an induced trip is somewhat less clear-cut. While it has been successfully demonstrated that walking speed has no effect on the impact location of an induced trip [Smeeters et al.], there is evidence from a number of studies to suggest that walking speed can significantly affect a subject's ability to successfully recover following a trip [Pavol et al. 1999b].

Studies carried out on older subjects have provided contradictory data on the effect of walking speed on trip outcome. Work by Pavol et al. with healthy older adults found that those most likely to fall when tripped exhibited a brisk purposeful gait, with a faster walking velocity and longer stride length. These gait characteristics were found a better predictor of which individuals would fail to recover from an induced trip than any other variable such as age or gender [Pavol et al. 1999b]. This would appear to indicate that a fast walking speed is a key risk indicator for trip falls among the elderly, and would suggest that older adults could reduce their chances of falling following a trip by simply taking their time while walking. However these findings are at odds with the conclusions of epidemiological studies. These studies have shown a slow gait and shorter stride length to be strongly associated with an increased risk of falling among the elderly [Nevitt et al., Murray et al.].

It has been argued that this apparent contradiction might be explained by the fact that epidemiological studies do not always differentiate between trip induced falls and falls for other reasons such as slipping and the risk factors for other types of fall may be very different than those for trips [Pavol et al. 1999a, Pavol et al. 1999b]. Although walking velocity is one of the many variables that have been associated with falls in older adults, it remains unclear whether slow walking velocity contributed to the injury risk, or was a protective adaptation to compensate for other risk factors [Bogert et al.].

Walking velocity contributes to the speed of forward rotation of the body after the trip, while response time determines the duration of this rotation before recovery initiated and it is suggested that both variables contribute to the orientation of the body when the recovery foot contacts the ground as follows:

$$Orientation \propto (Walking\ Velocity)(\mathrm{Re}action\ Time)$$

The orientation of the body at the time of recovery foot ground contact is proportional to the subject's walking speed and the subject's reaction time.

There is a critical body orientation beyond which it is too late to successfully initiate recovery, it may be argued that a subject may increase the time taken to reach this critical orientation by reducing their walking velocity at the time of tripping and thereby increasing the reaction time available to them in which to initiate a recovery attempt (although large reductions in walking velocity would be needed) [Bogert et al]. Although these arguments have been derived from studies carried out on older adults there is no underlying reason why they cannot be generalised to the entire healthy population.

It should be noted however, that although it is believed that reduction in walking pace would give an individual a greater window of opportunity to initiate a successful recovery from a trip and thereby reduce the likelihood of a fall and injury the work of Smeeters et al has shown that reducing the gait speed below a critical level (below 60 paces a minuet) can significantly increase the probability of a hip impact following a fall due to slipping. It appears therefore that there is a trade off to be made between giving an individual the best chances of recovering from a trip and minimising the chances of a hip impact following a fall due to a slip. This consideration is of particular relevance to elderly populations where the risk of hip fracture is greatest and should be borne in mind when considering advice to be given to the elderly.

Effect of Reaction Time on Trip Outcome

Research has shown that walking velocity contributes to the speed of forward rotation of the body after the trip, while response time determines the duration of this rotation before recovery is initiated [Bogert et al.]. The orientation of the body at the time of recovery foot ground contact, is proportional to both walking velocity and reaction time, see equation (1).

Biomechanical studies of falls resulting from induced trips have shown that there is a critical body orientation beyond which it is too late to successfully initiate recovery. It may be argued that a subject may increase their chances of a successful recovery attempt by reducing either their walking velocity or improving their reaction time.

Bogert et al. developed a model, which modelled the subject as a rigid body, which following the trip rotated about a fixed axis represented by the stance foot ankle joint. The model was validated by comparing the predicted pendulum kinematics to the experimental kinematics of the subjects previously reported by Pavol [Pavol et al 1999a].

The results of model simulations showed that the predicted body orientation was much more sensitive to reductions in response time that to reductions in walking velocity. It is suggested that subjects at risk of falling could achieve dramatic increases in their safe walking velocity by improving their response time and that a slow reaction time is a key risk factor for trip related falls. Although these arguments have been derived from studies carried out on older adults there is no underlying reason why they cannot be generalised to the entire healthy population.

Effect of Forewarning on Gait Pattern

In all the trip studies reported in the literature recovery reactions are compared with normal walking gait [Pavol et al.1999b , Owings et al., Smeeters et al., Bunterngchit et al.]. For ethical reasons, the subjects were informed of the purpose of the study and warned that attempts would be made to trip them. This raises the question whether and how subjects change their walking pattern when they are forewarned of a possible trip and if any such gait modifications could affect the validity of the study findings. Pijanappels et al. investigated this possibility; they investigated the effect of forewarning of a possible trip on the gait pattern of healthy young adults.

Gait analysis was used to divide the subjects walking pattern into temporal components (velocity, step frequency, stride cycle time, stance time, and swing time) and spatial components (stride length, step width, minimum toe clearance). Researchers found that forewarning the subjects of a possible trip had no effect on the temporal parameters of their stride pattern, but it did have a significant effect in the spatial parameters. Analysis of the motion capture data, showed that warning the subjects resulted in a small increase in step width (5.3%) and a significant increase in the minimum toe clearance (51.6%) [Pijanappels et al.].

The fact that the subjects increased their minimum toe clearance from 2.19 cm to 3.32 cm after the warning is intuitively sensible. In obstacle avoidance, strategies are required to minimise the risk of interference with an obstacle. Research has shown that foot-obstacle clearance is increased in comparison with normal foot-floor clearance, even when the obstacle is no more than tape on the floor [Austin et al., Chen et al.]. Gait analysis has shown that the heel or midsole was most frequently the lowest point of the foot when crossing and obstacle, this is believed to carry less risk for a forward fall in the case of contact than when the toe contacts the obstacle first [Chen et al., Pijanappels et al.].

Forewarning if a potential trip has been clearly demonstrated to have an affect on the subject's gait in terms of spatial parameters, however researchers believe that these gait modifications are not expected to alter the probability of tripping, nor the recovery reactions taken after gait disturbance [Pijanappels et al.]. Researchers therefore suggest that these gait modifications will not affect the validity of trip study findings. It should be noted, that in the studies reviewed by Pijanappels et al. the obstacles used to trip test subjects ranged in size from 5.1 cm to 15 cm which were many times larger that even the modified minimum toe clearance. If it was proposed to conduct a trip study utilizing obstacles comparable to the "normal" minimum toe clearance to induce gait disturbance it is possible that the 50% increase in minimum toe clearance could significantly impact on results, and the findings of studies using small obstacles should be treated with appropriate caution.

Minimum Toe Clearances

Information in the literature on the minimum toe clearance of healthy younger people is limited as research activity has concentrated on the elderly and other vulnerable populations [Pavol et al. 1999b, Pavol et al. 2001, Owings et al., Bogert et al., Davis et al.]. A review of the available literature showed, that there is a considerable discrepancy between the reported values of minimum toe clearance, see Table 1.

Author	Minimum Toe Clearance (mm)	Sample Size
Bunterngchit et al.	12.9	10
Pijanappels et al.	21.9	15
Winter	8.7	11

Table 1 Table comparing reported values of minimum toe clearance for healthy young adults.

In the studies referred to in Table 1 gait kinematics were recorded by means of high speed video cameras, and the subjects motion was tracked by means of markers placed on key anatomical landmarks. The minimum toe clearance was calculated by plotting the trajectory of the toe marker, and averaging it over a number of walking trials, and a number of subjects.

A possible explanation for the factor of two difference in the reported values of toe clearance healthy young adults is differences in the positioning of the toe marker. No precise description, or figures showing how the position of this key marker was determined was given in any of the papers, and it is not possible to know if the markers can be considered equivalent across all three studies [Bunterngchit et al., Pijanappels et al., Winter].

Of these three studies into toe clearance Bunterngchit et al. were the only ones to impose a cadence (100 steps/min) on their subjects. In the other research volunteers were allowed to self-select a natural comfortable walking pace, however this appears to have had no significant effect on the measure toe clearance values.

Given the spread of toe clearance values available in the literature, it would appear that it is reasonable to assume an average toe clearance of 14.5 mm for healthy young adults. *Given the small sample sizes used in all of these studies and the different values of toe clearance obtained it is clear that further research is required in this area to establish a value for minimum toe clearance with greater confidence.*

Although there is disagreement in the literature regarding the value of toe clearance among the fit and healthy, researchers are generally agreed that toe clearance decreases with increasing age [Bunterngchit et al., Winter et al., Austin et al., Davis et al., Woolley et al.]. Studies comparing the gait of health young and old individuals showed that age could reduce the toe clearance by up to 13% [Winter et al.]. The precise rate of decline in toe clearance with age in healthy individuals is unclear and is a potential area for future research. It is unclear for example if the on set of decreased toe clearance corresponds to the increase in trip accidents seen among women after the age of 45 [Davies et al., Manning].

Conflict with Tactile Paving

There are a number of draft standards for tactile paving currently under development [BSI2002a, BSI2002b]. The aim of tactile paving is to convey information to visually impaired people about their environment, specifically to warn them of a hazard such as a kerb of platform edge immediately ahead. It is intended that the type of profile on the paving, such as blisters or corduroy banding, would provide disabled individuals with information about the type of hazard ahead.

In the draft standards currently under discussion the proposed height of the tactile profiles varies between 5 and 6 mm. The estimates for the average toe clearance available in the literature varied widely see Table 1. It should be remembered that the values reported were averages and that a proportion of the test subjects may have toe clearances significantly smaller than these average values. This would be of particular concern if the 8.7mm value for average toe clearance determined by Winter is an accurate representation of the general public. This would imply that the proposed 5 to 6 mm height of the tactile profiles could potentially interfere with the normal walking gait of a significant number of individuals and would be of particular concern for those people who are unable to pick up the visual colour warnings designed to alert pedestrians to the paving's presence.

It is therefore possible that the tactile paving may pose a significant trip hazard specifically to those individuals it has been designed to aid. This is especially concerning as biomechanical studies have shown that tripped individuals tend to fall forwards and this may result in pitching a pedestrian into the path of the hazard they are being warned about. Given the increasing use of such paving materials a better understanding of the mechanics of how obstructions of this size interfere with the gait of both impaired and unimpaired individuals is required.

Effect of Age on Risk of Falling

Numerous epidemiological studies into trips and falls are reported in the literature [Anderson and Lagerlöf, Kemmlert and Lundholm 1998, Buck and Coleman, David and Freedman, Davis et al., Manning et al.]. These studies serve to highlight the massive cost of STF accidents in terms of both economics and human pain and suffering.

Analysis of accident statistics has shown that unlike other types of accidents, the occurrence of STF accidents increases with age, especially among women [Buck and Coleman, Kemmlert and Lundholm 1998, Davis et al.]. It has been argued that increase of trips with age may be accounted for in two ways:

1. An increase in the individual's intrinsic risk of falling, particularly in the case of women [Kemmlert and Lundholm 1998, Davis et al.].
2. Mature individuals are more likely to suffer an injury that causes them to attend hospital, or that makes the accident notifiable than are their younger counterparts [Anderson and Lagerlöf, Kemmlert and Lundholm 1998, Davis et al.].

The increase in STF accident with age among women have commonly been attributed to postmenopausal changes and generally considered to be a problem associated with the elderly. Detailed analysis of occupational accident statistics and surveys of patient attending accident and emergency units have shown that a dramatic increase in the numbers of women suffering serious injuries and fractures as a result of underfoot accidents occurs between the 49 and 51 years of age [Kemmlert and Lundholm 2001, Davis et al.].

It has been suggested that the increase in fractures in postmenopausal women due to underfoot accidents is a result of osteoporosis weakening their bones, however the on set of osteoporosis is gradual and the discontinuous increases in the studies cannot be explained by increased risk due to osteoporosis of fracture alone [Davis et al., Manning].

Biomechanical studies of trips have shown that reaction speed, muscle strength, and balance are all factors, which can influence and individual's ability to successfully recover from a trip. The menopause is known to adversely affect women's muscle strength, muscle mass, and work by Wojicik has shown that older women are less able than younger women or older men to recover their balance by taking a single step during a forward fall, apparently due to reduced maximum speed of foot movement.

Studies by Pavol et al. indicate that healthy elderly individuals have a relatively low chance of falling as a result of a single trip, approximately 13%. They have suggested that the discrepancy between the number of trip accidents seen among elderly men and women arises not from women having a worse chance of initiating a successful recovery, but from the fact that elderly women trip much more frequently than men [Pavol et al 1999a, Pavol et al 2001]. This suggestion raises the question of why women are so much more susceptible to trips than men?

The physiological postmenopausal changes describe above all combine to reduced the probability of older women executing a successful recovery following a trip, but it seems unlikely that these changes alone could account for the dramatic increase of trips seen in older women. Toe clearance has also been shown to reduce with age [Winter] and would result in a corresponding increase in trips, given that the ability of older women to successful recover it might there be reasonable to expect them to fall more frequently. If toe clearance is reduced more with age among women than men this would further exacerbate the situation.

Gait pattern and firm support from the stance leg has been shown to be important in the ability to recover from an induced trip. Those mostly likely to fall had a faster walking speed and longer stride length compared to their height. Women who habitually match their stride patterns to that of male companions by increasing their stride length may inadvertently be reducing their chances of recovery should they suffer a trip, and while young women with their faster reaction times may still be able to recover older women may no longer be able to do so successfully.

It is probable that footwear also plays a significant role both in gait modification to avoid tripping hazards and in the ability to recover from a trip. Researcher have shown that individuals forewarned of a tripping hazard modify their gait patterns by increasing the toe clearance by up to 50% and choice of foot wear will clearly have an impact on how the foot and ankle joints may be flexed.

Choice of footwear will also clearly have an impact on the stability of the stance leg during the execution of the recovery attempt, which will in turn affect the likelihood of success. It is probable that the high heels often favoured by women would have a detrimental effect on a woman's ability to modify her gait to avoid trip hazards making her more likely to trip, and on the stability of her stance leg during a recovery attempt making it less likely to succeed. In older women where physiological factors have already compromised their ability to recover from trips footwear may have a significant role to play in trip accidents.

The effect of age on the incidence of trip accidents is clearly a combination of many factors including physiological changes and “lifestyle” choices. The ways in which many factors interact is complex and not readily extracted from the available literature covered in this review and provides scope for further investigation.

Experimental Set-Up

The papers reviewed in this literature survey can be divided into two categories; those with practical subject-based methodologies and those that rely on written and recorded data.

Two of the papers studied involved analysis of reports from the Swedish Occupational Injury Information System [Kemmlert et al] and Coroners reports [Cayless]. Over 1000 reports were analysed in both papers, to allow a reliable statistical analysis to be carried out. HSL has previously carried out a study that analysed RIDDOR information using SPSS software, which was similar to the above papers [Dickety].

Many similarities exist between the eight experimental procedures looked at as part of this review. In all experiments a defined walkway is used, most commonly a straight area of flooring on which the subjects walk forward, see Figure 3, in one example used a circular track was used [Bunterngchit et al], although the basic principles are the same.

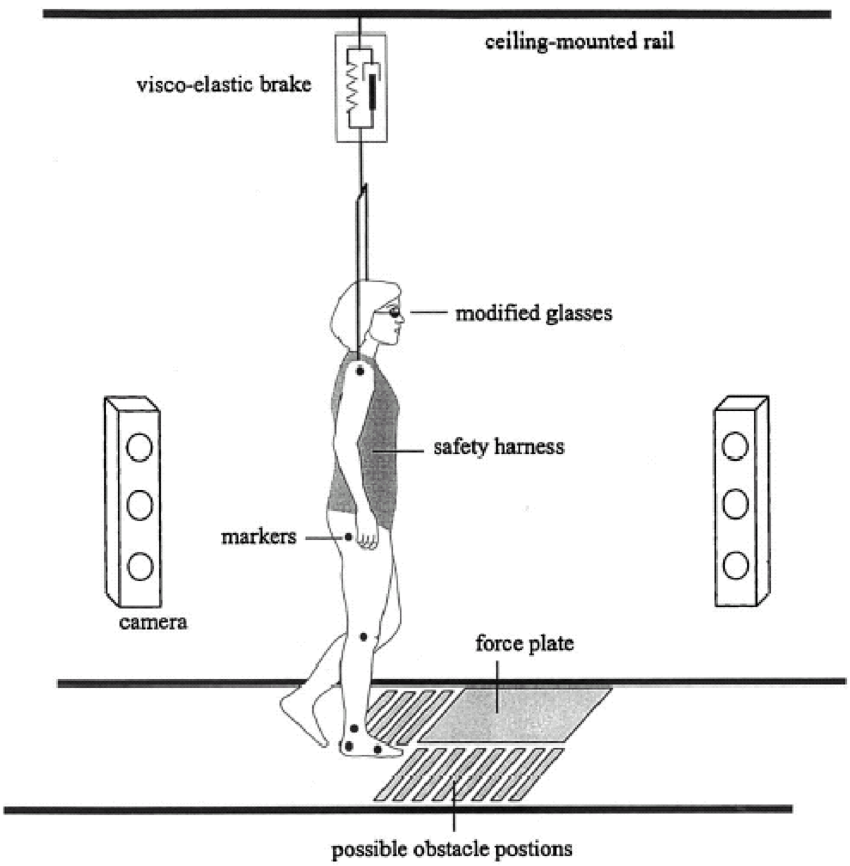

Figure 3 Schematic diagram showing a generic trip study experimental set-up, including a walk way, force plate, trip hazard, fall arrest system, motion capture markers, and video cameras [after Pijnappels et al.].

Half of the experiments incorporate a fall arrest system, each one consisting of nothing more than a body harness attached to an overhead bearing. This then allows the subject to fall for a defined distance before arresting and stopping the fall. Two of the experiments used no fall arrest systems at all, at least none that were mentioned in the paper. However, one of the papers wasn't involved in instigating a trip, it seemed to be more concerned with measuring toe and heel clearance when considering different obstacles [Austin et al]. The last paper used the cushioning effect of soft mats to protect subjects from falls [Smeesters et al]. The walkway was bordered either side by mats and an additional mat was positioned on the walkway near the end and within reach of the subject to protect against forward falls. A spotter was also on hand to carry a mat behind the subject in case of a backward fall. In addition to these measures, subjects were also asked to wear wrist and knee pads.

All of the experimental papers studied used some sort of motion capture system using reflective or light emitting markers on anatomically significant body positions to allow the simulated motion of the body to be studied.

HSL have considerable experience in gait analysis, and the high speed video motion capture facilities already exist within the laboratory. A detailed biomechanical analysis of both successful and unsuccessful attempts to recover from trips would therefore be within the scope of HSL’s existing expertise.

Methods of Inducing Trips

There are several ways of inducing trips:

- Cuffs - one study involved fitting subjects with an ankle cuff attached to a cable. The subject would be allowed to travel freely down the walkway until the spooling of the cable was interrupted, thereby arresting the subject's leg and causing them to fall. The location of the trip was varied along the walkway so as to maintain some degree of surprise.

- Pneumatically Driven Objects - two very similar studies, by the same authors, concentrated on pneumatically driven obstacles as a way of inducing trips. The obstacles were concealed under the walkway and, when triggered manually by the operator, the obstacles rose to approximately 5cm from the floor, obstructing the toe of a shoe. Also, a decoy "tripping rope" was laid to provide a visible hazard so as to mislead the subject. Only one attempt was made to trip the subject.

- Stationary Obstacles - there was only one experiment to use stationary obstacles [Austin et al.]. Wooden obstacles were made of various heights to mimic "real" obstacles, for example a curb or doorstep. However, it seems no attempt is made to actually instigate a trip, but to measure the minimum toe/heel clearance amongst other parameters.

Typical subject numbers in the experimental papers vary greatly. Zhou et al. uses only one subject (male), while at the other end of the scale Pavol et al. uses 79 subjects (50 female, 29 male) in both of their papers. The remaining three papers all use between 14 and 20 subjects of differing ages and genders. This seems to be a much more manageable number of subjects.

The experimental procedures described above have not been attempted before at HSL but the majority of methods would probably be suitable for use at HSL given the available facilities.

It is fair to say some sort of fall arrest system would need to be in place to protect test subjects, as a matting system alone probably would not be adequate enough to satisfy the needs of an ethics committee. HSL is familiar with the use of such systems, and the installation of one similar to those described in many of the papers would not be a problem. It could also be possible to attach a load cell onto the fall arrest ropes to determine the force exerted by the different subjects allowing experimenters to differentiate between successful attempts to recover from trips and rope assisted recoveries.

To actually induce the trips the least disruptive method would be to use stationary obstacles. This may be unfeasible though as it takes away the element of surprise to the subject, therefore altering their gait. To combat this problem the subjects could be limited to restricted vision, to try to prevent the subjects from spotting the obstacles, or dummy obstacles such as tapes on the floor could be used to visually distract the volunteers.

Pneumatically driven obstacles are a good idea and do not contain any of the problems associated with stationary obstacles. However, significant modifications to the existing walkway would be necessary as well as the design and purchase of the actual tripping system which would have to be budgeted for in any research proposal.

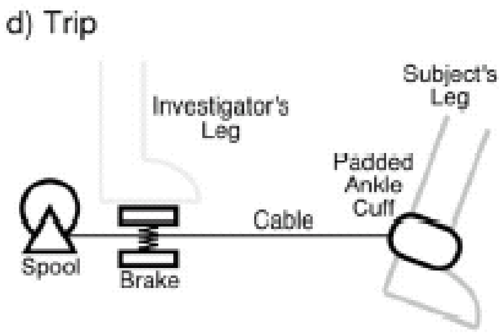

Figure 4 Schematic diagram of the cuff method of inducing trips as used by Smeeters et al [after Smeeters et al.].

Using a cuff mechanism, as shown schematically in Figure 4, would also be fairly undisruptive to the existing set up, but an ethics committee may have concerns over this method. Although there is no indication in the paper as to any potential problems arising to the subjects' ankles or legs during or after the experiment, the possibility of a subject obtaining an injury cannot be ruled out.

While the cuff method of inducing trips appears to pose the least difficult to integrate with the exiting set up as it would not require any substantial modification of the existing walkway questions regarding its suitability remain. The main focus of the studies where the cuff method was used to induce falls was to study the biomechanics of the falls themselves and to determine the typical impact locations resulting from trips [Smeeters et al.]. This test methodology does not provide data on the mechanics of how obstacles interfere with gait, or on the types and size of obstacles most likely to be problematic. Given HSL's interest in trip causation, not merely the biomechanics of a fall resulting from a trip it is the authors opinion that this method of inducing trips would be unsuitable for use by HSL.

The current review has highlighted a significant difference in approach to the study of trips and trip causation between Europe and America. In Europe the main focus of research to date appears to be statistical analysis and detailed reviews of accident reports, coroners reports and hospital attendance [Dickety, Cayless, Anderson and Lagerlöf, Davis et al.]. While such epidemiological studies are also carried out in America they appear to have a more proactive view of trip research, all the studies of induced trips mentioned in this review were undertaken by research groups based in either America or Canada.

While epidemiological studies undoubtedly provide invaluable information about accident trends in the population in general, severity of injury and the effectiveness of accident prevention programs they do not provide data about the mechanics of how trips occur or even the type of obstacle responsible for initiating the accident. The type of induced trip research currently being carried out in North America allows them to develop a more fundamental understanding of the biomechanics of trips, recovery strategies, the effect of gait speed on likely impact locations, and the trip risk factors in gait patterns that cannot be obtained from epidemiological studies alone. If HSL were to undertake a similar study it would present HSL, and by extension HSE, the opportunity to establish themselves as the European centre of expertise for this type of trip research.

Suggested Future Research

A variety of methods for inducing trips in subjects under laboratory conditions have been identified from the literature. The fact that we would be forcing people to trip and potentially fall means that a full ethics submission would be required, and the committee may have concerns over possible injuries particularly if a wide age range of subjects were used. It is therefore suggested that for the initial phase of research there are other issues that can be addressed without the need to induce trips in subjects.

The wide variation in toe clearance values available in the literature for young healthy individuals indicates that clarification is needed in this area. It would be highly desirable to gain a better understanding of the variation of toe clearance among the population, and how it is effected by variables such as gender and age.

If the variation of toe clearance across the population was better understood it might be possible to establish a minimum toe clearance level above which 1 in 100,000 or 1 in a million individuals would encounter difficulties in much the same way as the BRE work in the 1950's established minimum friction coefficient of friction level to minimise the risks of slip accidents [Pye and Harrison]. This minimum toe clearance level might then be used as a guideline for the maximum level of unevenness in supposedly level floor areas. Areas where greater levels of unevenness are to be routinely found, such as cobbled regions should be clearly demarked to give pedestrians clear visual cues as to the increased trip risk as research has shown that pedestrians will unconsciously modify their gait to increase the toe clearance when they are aware of a likely trip hazard [Pijnapplels et al.].

Toe clearance data could potentially be collected by means of gait analysis of subjects using motion capture techniques and the high-speed video facilities available at HSL. Although these facilities have not previously been used to collect toe clearance information it is believed to be within the capabilities of the equipment.

It is therefore recommended that the next step in the proposed trip project should be to carry out a limited scoping study to confirm that:

- The existing HSL facilities are suitable for the reliable collection of toe clearance data
- Assess the time required to mark up each test subject for motion capture
- Assess the time required to carry out the gait analysis
- To determine repeatability – How much does an individuals toe clearance vary between runs

Summary

A review of the literature has shown that trip accidents account for between 25 and 33% of reported slip, trip and fall accidents. Analysis of HSE RIDDOR statistics indicates that trips account for between 8,000 and 12,000 reportable accidents each year.

Biomechanical studies of induced trips have shown that when the tripped individuals make no attempt to save themselves, a trip will always result in a forwards fall with frontal impact regardless of the gait speed.

Three common strategies for recovering from a trip have been identified from the literature:

1. Lowering strategy – In a lowering strategy the tripped foot is immediately lowered to the ground on the near side of the obstacle. The tripped limb then acts as the support limb as the collateral support limb executes the initial recovery step across the obstacle. This strategy is only observed in response to late swing perturbations.
2. Elevating strategy – In an elevating strategy the tripped limb is used as the recovery limb as the tripped foot is lifted over the obstacle in a continuation of the original step. The collateral stance limb acts as the support limb during the recovery step. Recovery limb flexion occurs at multiple joints. The strategy was predominately observed in response to early swing perturbations.
3. Reaching strategy – As in the elevating strategy the tripped limb is used as the recovery limb. Elevating and reaching strategies are differentiated by the fact that in a reaching strategy recovery limb flexion occurs primarily at the hip. This strategy is generally observed in response to late swing gait perturbations.

Studies have shown that walking speed does not significantly effect the impact location of a fall resulting from a trip. There is a critical body orientation beyond which it is too late to successfully recover from a trip. It is generally argued that a higher walking speed results in the body having a greater angular momentum following a trip, therefore reducing the time available to react to a trip, and therefore increases the likelihood of a fall.

A reduction in reaction time will also improve the chances of initiating a successful recovery attempt as the body will have had less time to rotate and reach the critical orientation. Models developed by Bogert et al. predicted that body orientation was more sensitive to reductions in reaction time than walking speed indicating that people could significantly reduce their likelihood of falling following a trip by improving their reaction time.

Epidemiological studies of slip, trip and fall accidents have shown that the number of falls increases with age in both men and women, but that the increase is much more pronounced among women. This has traditionally been attributed to post menopausal changes reducing their ability to execute a successful recovery attempt and the onset

of conditions such as osteoporosis increasing the likelihood of them sustaining a reportable injury. However these physiological changes alone are insufficient to account for the increase in slips, trips and falls among women.

There is evidence in the literature, which indicates that postmenopausal women may trip more frequently than their male counterparts, and it may be argued that a combination of physiological and “life-style” factors can be used to begin to explain the higher frequency of trips among women, but limited information is available in the literature in this area.

Researchers have clearly demonstrated that subjects significantly modify their gait patterns when they are forewarned of a trip hazard, with the most marked change being a 50% increase in the subjects toe clearance. This finding does not call into question the validity of any the studies sited in this review, but it does indicated giving pedestrians clear visual cues when they are about to approach an uneven surface is an important measure in preventing trip accidents.

There is comparatively little data available in the literature on the toe clearance of healthy individuals, and there is significant scatter in the values reported, 8.7 – 21.9 mm. The sample sizes used the various studies were small and information how toe clearance varies with age and gender is lacking. It is suggested that this area be considered for future research.

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