Pedestrian Speeds on Stairs
- An Initial Step for a Simulation Model -

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Abstract

In order to predict a pedestrian's walking speed on stairs from his/her characteristics of and those of the stairs, the relationship between the walking speed of a pedestrian on stairs and his/her characteristics, and the relationship between the pedestrians' walking speeds on stairs and the stair-gradients were investigated. It is suggested that Leg Extensor Power shows a strong correlation to walking speeds of elderly people on stairs, the stair-gradient has a linear relationship with horizontal walking speeds on stairs, and Leg Extensor Power could be used to represent a unique walking speed of an elderly pedestrian on stairs.

Keywords: Pedestrian, Walking speed, Stair, Elderly pedestrians, Leg extensor power (LEP), Stair-gradient, Predicting walking speeds

Definition of words, abbreviation

In this paper, we define some usage/abbreviation of words as follows. Fig.1 is a schematic representation of horizontal/vertical/ inclined distance.

Horizontal walking speed

= (Horizontal distance) ÷ (Used time)

Vertical walking speed

= (Vertical distance) ÷ (Used time)

Inclined walking speed

= (Inclined distance) ÷ (Used time)

LEP: Leg Extensor Power (unit: Watt)

Walking patterns:

In the experiment, we have four walking patterns, namely normally ascending, normally descending, fast ascending and fast descending.

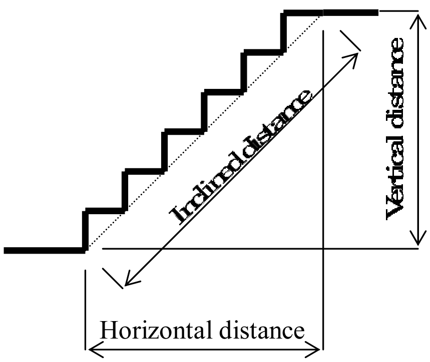

Fig 1. Definition of distance

1. INTRODUCTION

1-1. Background

Understanding movements of pedestrians is essential to plan and design transport facilities. Hitherto, many studies of pedestrians have been conducted, and the walking speed has been one of the major topics in that research. Research on this issue has been basically observational and has regarded pedestrians as a flow: e.g. (Hankin and Wright, 1958), (Older, 1968) and (Daly *et al*, 1991). Only a limited number of studies have been done on the walking speed of pedestrians and their characteristics with the intention of designing pedestrian crossings (signal timing) (e.g. Bennett *et al*, 2001). Their findings were that people aged 62-65 yr or more walk more slowly than younger people: (Knoblauch *et al*, 1996), (Peschel, 1957), (Tregenza, 1976), and that the walking speed of women tends to be lower than that of men (Peschel, 1957). While these studies focused on walking speed on a flat surface, Fruin (1971) looked at the walking speeds of pedestrians on stairs. (Fruin's results are compared with ours in the discussion section of this paper).

In physiology, several studies of the walking speed on a flat surface have been conducted in laboratory environments. They have investigated factors affecting the walking speed. Himann *et al* (1988) reported that the walking speed was associated with height before 62 yr old, and with height and age after 62 yr old. Bendall *et al* (1989) suggested that calf strength and some other factors accounted for the walking speed. Although there have been studies of the walking speed on a flat surface, physiological research has seldom considered the walking speed on stairs. Physiological interest has gone rather to the maximum climbable riser-height of a single step: e.g. (Voorbij and Steenbekkers, 1998). In architecture, Templer (1992) proposed an equation to predict the walking speed on stairs based on the proportions of stairs, namely riser-height and tread-length. However, he did not consider the characteristics of pedestrians, and the background for the equation is obscure.

Some indices have been used to describe strength or outputs of leg muscle. Among them, Bassey *et al* (1992) showed that Leg Extensor Power (LEP) was well correlated with the walking speed on a flat surface with r = 0.80 among elderly people. The relationship between LEP and the walking speed on a flat surface was examined also by Mockett *et al* (1996), who found a significant relationship between LEP and categorised descriptors of the walking speeds, where the sample size was 1980. There has been a study on the relationship between LEP and the speed of a stair climbing activity among elderly people (Bassey *et al*, 1992). However, this result could not infer a direct relationship between the walking speed on stairs and LEP because the experiment did not distinguish between ascending and descending speeds, and the stairs in the experiment consisted only of four steps. This was understandable in the light of Bassey's primary aim, which was to validate LEP by examining relationships between LEP and various physical performances, one part of which was stair climbing.

1-2. Objectives of this research

This paper focuses on the relationship between the characteristics of pedestrians and their walking speed in order to predict pedestrians' walking speed by their characteristics. We concentrate on the walking speed on stairs because stairs are a critical path in multi-floor transport facilities in terms of being a barrier both for elderly people and for the evacuation of all pedestrians. Especially, we are interested in the characteristics of pedestrians related to ageing because of the expectation that more elderly people may use public transport facilities, and their walking characteristics may be different from those for younger people. Based on existing studies of walking speeds on a flat surface, it is hypothesised that LEP may show a relationship with the walking speed on stairs. Also, we presume that the proportion of stairs may influence the walking speed on the stairs. We select the stair-gradient as an index of the stair proportion, and examine the relationship between the walking speed and the stair-gradient. Obtained knowledge/data will be of use in our heterogeneous simulation model of pedestrians, which can represent a variety of pedestrians including the elderly.

2. METHOD

Data were drawn from two study groups.

Group 1) 6 healthy men and 12 healthy women, aged between 60 and 81. The participants were recruited at meetings of societies for elderly people. All of them could walk and ascend/descend stairs in their daily lives without any significant problems.

Group 2) 7 healthy men and 8 healthy women, aged between 25 and 60. They were students and staff at University College London.

In the first stage of the experiment, each participant's personal characteristics, namely height, weight and LEP were measured. To measure LEP, we used the leg power rig, developed by University of Nottingham, with which LEP can be measured without any medical operation. The measurement procedure of LEP was in line with Bassey and Short (1990). Each participant's age and any current significant health problem were obtained by means of a questionnaire.

After the measurement stage, each participant was instructed to ascend/descend four sets of stairs, as well as to walk on a flat surface, inside buildings of University College London. A description of the stairs is given in Table 1. Each set of stairs consisted of one flight. All participants wore comfortable clothes and flat walking shoes. At each set of stairs, the participants were asked 1) to ascend the stairs at his/her normal speed, 2) to descend at his/her normal speed, 3) to ascend at his/her fast speed, and finally 4) to descend at his/her fast speed. Participants could use the handrail and miss stairs according to their preference. Between procedures 2) and 3), participants took a rest sitting on a chair for more than two minutes so that fatigue would not affect the results. The time taken to ascend/descend the stairs was measured by a stopwatch to calculate the walking speed. In order to avoid any effects from acceleration, participants were asked to start walking on the landing one metre before the first stair, and to finish walking one metre after the last stair. For the walking speed on a flat surface, participants were asked to walk twice for each normal and fast speed, and the averaged time was used to calculate the walking speed.

Table 1. Characteristics of the stairs used in the experiment

Stair No.	Number of steps	Proportion			Total length		Availability of handrail
		Riser-height	Tread-length	Stair-Gradient	Horizontal length	Vertical length	
		mm	mm	deg	m	m	
Stair1	12	185	230	38.8	2.76	2.22	✓
Stair2	12	175	250	35.0	3.00	2.10	✓
Stair3	15	157	267	30.5	4.01	2.36	✓
Stair4	9	152	332	24.6	2.99	1.37	✓
Flat surface		-			8.00	-	×

3. RESULTS

3-1. Physical characteristics

The participants' physical characteristics are displayed in a summary form in Table 2. The significance of difference was tested by unpaired *t* tests. Between the two study groups, there was a significant difference in age, height and LEP. No participant reported notable illness affecting his/her walking on stairs. One participant in Group 1 was not able to ascend/descend No.2 stairs at her fast speed. A wide variation of LEP was observed both in Group 1 and in Group 2.

Table 2. Characteristics of the participants

	Group 1	Group 2	Significance of difference
Sample number	18	15	-
(male sample)	6	7	-
(female sample)	12	8	-
Age (yrs)	71 ± 5.9	34.5 ± 12.7	<0.001
Height (cm)	161 ± 7.2	174 ± 8.2	<0.001
Weight (kg)	67.3 ± 11.7	66.4 ± 13.9	NS
LEP (W)	64.1 ± 38.6	197.7 ± 78.5	<0.001

Results are given as mean ± SD.
Significance of difference tested using unpaired *t* tests.
NS = not significant

3-2. Performance

Performances of the participants are shown in Table 3. The significance of difference was tested by unpaired *t* tests. More significant differences were observed for ascending/descending at fast speed than at normal speed.

Table 3. Horizontal walking speeds of the participants (unit: m/s)

Patterns of speeds	Stairs		Group1	Group2	Significance of Difference
	Stair No	Degree			
Normally ascending	Stair 1	38.8	0.44 ± 0.12	0.48 ± 0.10	NS
	Stair 2	35	0.52 ± 0.12	0.56 ± 0.13	NS
	Stair 3	30.5	0.59 ± 0.13	0.63 ± 0.14	NS
	Stair 4	24.6	0.73 ± 0.17	0.76 ± 0.17	NS
Normally descending	Stair 1	38.8	0.47 ± 0.13	0.59 ± 0.14	<0.05
	Stair 2	35	0.58 ± 0.16	0.65 ± 0.14	NS
	Stair 3	30.5	0.64 ± 0.15	0.74 ± 0.17	NS
	Stair 4	24.6	0.80 ± 0.23	0.87 ± 0.19	NS
Fast ascending	Stair 1	38.8	0.61 ± 0.18	0.78 ± 0.24	<0.05
	Stair 2	35	0.69 ± 0.20	0.91 ± 0.31	<0.05
	Stair 3	30.5	0.79 ± 0.20	0.97 ± 0.28	<0.05
	Stair 4	24.6	1.00 ± 0.23	1.16 ± 0.31	NS
Fast descending	Stair 1	38.8	0.62 ± 0.17	0.87 ± 0.20	<0.001
	Stair 2	35	0.70 ± 0.18	0.92 ± 0.19	<0.01
	Stair 3	30.5	0.84 ± 0.18	1.08 ± 0.23	<0.01
	Stair 4	24.6	1.01 ± 0.26	1.18 ± 0.20	<0.05
Normal walking on a flat surface			1.31 ± 0.23	1.40 ± 0.17	NS
Fast walking on a flat surface			1.71 ± 0.29	1.84 ± 0.15	NS

Results are given as mean ± SD.
Significance of difference tested using unpaired *t* tests.
NS = not significant

3-3. Relationship between the walking speeds on stairs and the walking speeds on a flat surface

The correlation between the walking speed on a flat surface and the horizontal walking speed on stairs is displayed in Table 4. The results for Group 1 showed a strong correlation regardless of the walking patterns.

Table 4. Correlation coefficients between horizontal walking speed on stairs and on a flat surface

	Group 1		Group2	
	Walking on a flat surface		Walking on a flat surface	
	Normal speed	Fast speed	Normal speed	Fast speed
Normally Ascending	0.90	0.80	0.52	0.41
Normally Descending	0.73	0.67	0.46	0.55
Fast Ascending	0.70	0.85	0.55	0.77
Fast Descending	0.72	0.74	0.68	0.78

3-4. Relationship between the walking speeds and physical characteristics

The correlation between horizontal walking speeds and physical characteristics is presented in Table 5. To illustrate the comparison, we have selected Stair 2, as this stair-gradient is the steepest within the UK building regulations (DETR, 1998). LEP showed a strong correlation with all speeds in Group 1, whereas age and other characteristics did not. Fig.2 shows the relationship between LEP and the horizontal speed for ascending at a normal speed. Although there may be a linear relation between LEP and walking speed in Group 1, this is not so clearly the case in Group 2. Fig.3 displays the relationship between speed and age. No obvious relation was suggested between age and walking speeds in either group. These trends were confirmed also in other sets of stairs.

Table 5. Correlation coefficients between physical characteristics and horizontal walking speeds on Stair2 and walking speed on a flat surface

		Group 1					Group2				
		Age	Weight	Height	LEP	LEP/weight	Age	Weight	Height	LEP	LEP/weight
		(yr)	(kg)	(cm)	(W)	(W/kg)	(yr)	(kg)	(cm)	(W)	(W/kg)
Speed on stair 2	Normally Ascending	-0.34	0.03	0.08	0.79	0.76	-0.23	-0.25	0.12	0.23	0.17
	Normally Descending	-0.37	0.04	-0.09	0.68	0.71	-0.07	-0.60	-0.09	-0.05	-0.03
	Fast Ascending	-0.14	0.18	-0.02	0.76	0.82	-0.43	-0.07	0.29	0.37	0.27
	Fast Descending	-0.32	0.25	0.09	0.71	0.71	-0.20	-0.22	0.17	0.36	0.37
Speed on a flat surface	Normally	-0.23	0.23	0.16	0.89	0.82	-0.11	0.11	0.25	0.52	0.58
	Fast	-0.14	0.41	0.03	0.81	0.80	-0.45	-0.20	0.15	0.24	0.23

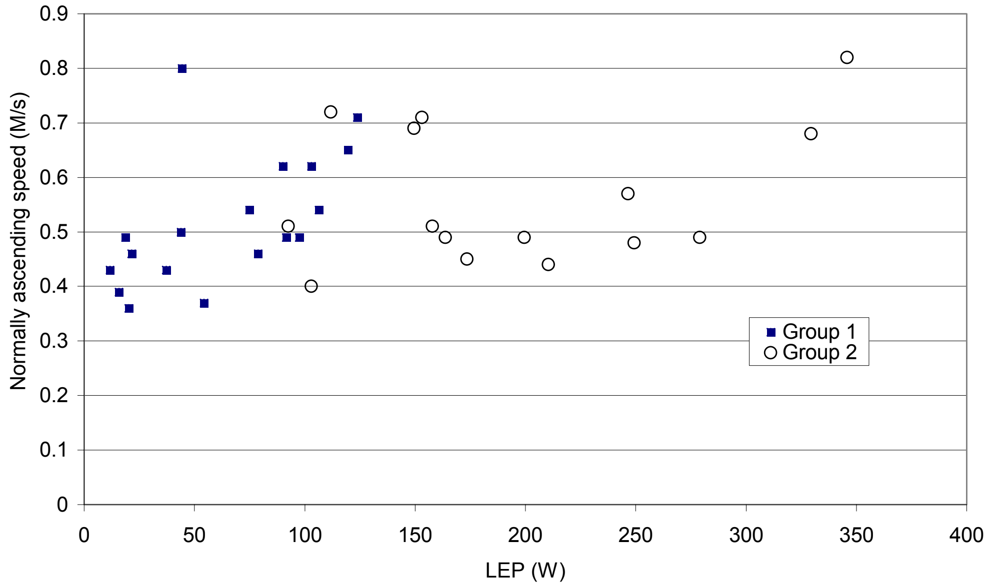

Fig 2. Relation between LEP and normally ascending speed (horizontal speed, Stair 2)

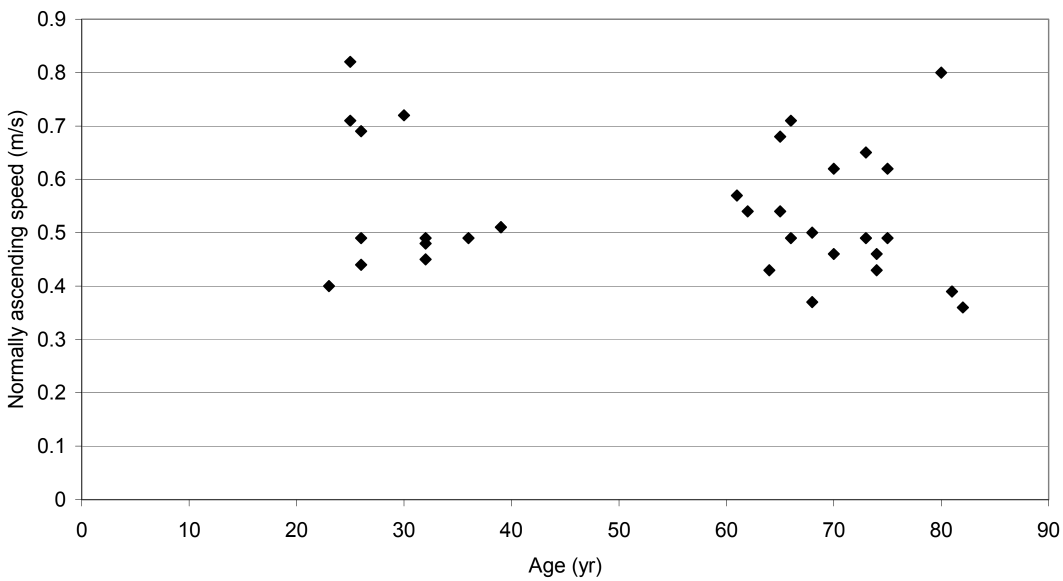

Fig 3. Relation between age and normally ascending speed (horizontal speed, Stair 2)

3-5. Relationship between walking speeds on stairs and stair characteristics

Fig. 4 shows the relationship between stair-gradients and the study groups' mean ascending speeds: horizontal/ vertical/ inclined speeds at both normal and fast speeds to ascend Stair 2. The results suggested a linear relationship between the stair-gradient and the horizontal walking speed. This trend was also confirmed in other walking patterns in the other sets of stairs.

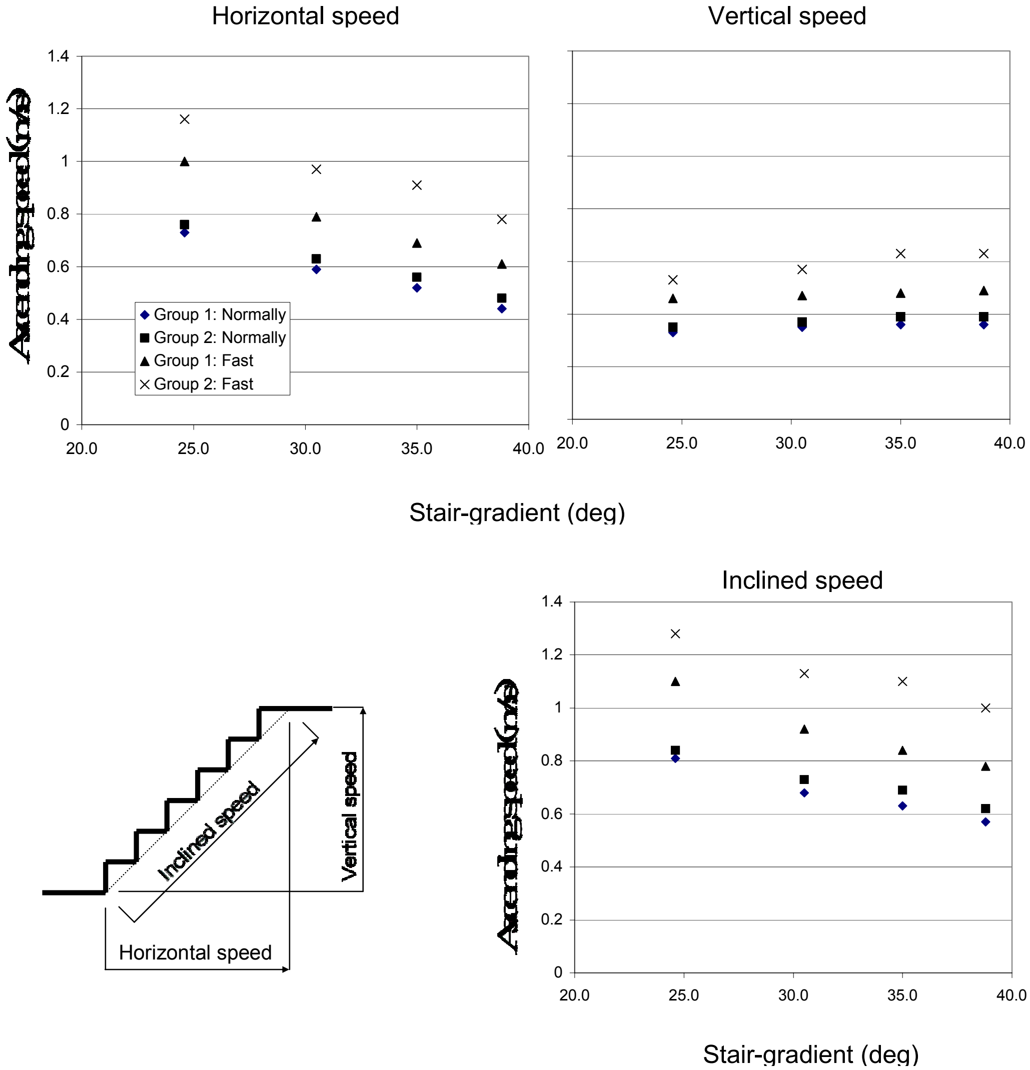

Fig 4. Relation between stair-gradients and ascending speeds on Stair 2: Horizontal/ Vertical/ Inclined speeds

4. DISCUSSION

The purpose of this study was to investigate the relationship between the walking speed and physical characteristics to predict the walking speed of a variety of pedestrians by their characteristics and the stair-gradient. The main results may be summarised by pointing out, first, that as shown in Table 5 LEP displayed a strong correlation with walking speeds of pedestrians on stairs among the elderly participants (Group1), whereas it did not among the young participants (Group 2). This result is similar to that in a study on the relationship between the walking speed on a flat surface and the leg strength (Buchner *et al*, 1996). These results can be explained by “reserved capacity” proposed by Buchner, where from 0 to a certain point (“threshold”) leg strength is necessary for a certain task and therefore the performance corresponds to the leg strength, but above this point further increase of leg strength does not necessarily improve the performance. As the young participants may have had a greater LEP than this required amount, they did not show a strong correlation.

Bassey *et al* (1992) used "LEP divided by weight" as an index to examine a leg power function, based on the assumption that during the performance leg power is used to move body mass, and consequently the index should be related also to the body mass. However, in our experiment "LEP" alone showed a higher correlation. Table 5 shows that in each walking pattern LEP alone has almost the same correlation coefficient for walking speed as does LEP/weight. For simplicity, we used LEP for the further analyse.

Height did not show a high correlation with the walking speed on stairs either in the elderly or the younger group. This contrasts with Himann *et al* (1988), which suggested that height was associated to the walking speed on a flat surface for all ages. On the other hand, Voorbij and Steenbekkers (1998) reported that whereas at the comfortable step-height the leg length had the most influence, at the maximum step-height age seemed to have the strongest influence. The results can be explained by assuming that for tasks which do not require much vertical movement of body mass, height is the dominant factor, but for tasks where body mass movement is essential, the importance of height becomes relatively small.

Age also failed to show a high correlation with the walking speed on a flat surface. The correlation efficient of our study was similar to that of Bendall *et al* (1989), which examined the relationship between the walking speed on a flat surface and a variety of indices. Meanwhile, LEP is supposed to have a strong correlation with the age. For simplicity, we may use only LEP for prediction of the walking speed in order to avoid the duplication of variables (Scalfia and Edholm, 1987).

An interesting result in our experiment was that the participants showed a high correlation between their walking speeds on a flat surface and on stairs. The choice of the walking speed is a function of the step frequency and the step length used (Himann *et al,* 1988). For walking on stairs, the step length is restricted by tread length of stairs, unless people miss stairs. The strong correlation may mean that people use the same or similar step frequency both for stairs and for a flat surface.

Also, we have found that horizontal walking speeds may have a linear relationship with the stair-gradient. Inclined speed showed the same tendency, but we can consider that the inclined speed was affected by the tendency of the horizontal speed. Although we have not examined this relationship statistically because of the shortage of sample stairs, it may be reasonable to include the stair-gradient as a variable for the prediction of the walking speed on stairs.

The elderly participants showed a strong correlation between LEP and the walking speed, and therefore LEP can be a variable to predict their walking speed. However, the young participants did not show such a strong correlation between the walking speed and any personal characteristics. How can we predict walking speeds of young people? Given that the step length is restricted on stairs, the step frequency may be a dominant factor to decide the walking speed. One solution is to find a factor which determines step frequency, which may be an index of agility of the body. Cunningham *et al* (1982) reported that the speed of selected walking paces on a flat surface was associated with maximal aerobic power among people aged from 19 to 66. An index which describes an aerobic capacity may show a higher correlation with the walking speed on stairs. Sports Council *et al* (1992) has conducted a national fitness survey including these indices, but consideration of cultural differences may be necessary when using these data.

Comparison of mean walking speeds on stairs between this study and Fruin (1971) was not consistent (See Table 6). Fruin's result was slower than ours for the elderly group. One possible reason is the difference between individual laboratory experiments and observation in actual facilities where people also consider surrounding people. This suggests that in prediction of the walking speed on stairs it may be reasonable to take account of the effect of the surrounding people.

Table 6. Comparison between our results and Fruin (1971)

	Stair gradient	Ascending				Descending			
		Elderly		Young		Elderly		Young	
		Male	Female	Male	Female	Male	Female	Male	Female
This study	38.8	0.41	0.46	0.50	0.47	0.46	0.48	0.61	0.57
	35.0	0.50	0.53	0.57	0.56	0.60	0.57	0.62	0.67
	30.5	0.56	0.60	0.65	0.62	0.64	0.64	0.72	0.76
	24.6	0.68	0.76	0.77	0.75	0.80	0.80	0.82	0.91
Fruin (1971)	32	0.43	0.39	0.69	0.51	0.57	0.47	0.69	0.51
	27	0.41	0.45	0.81	0.65	0.60	0.56	0.81	0.65

Horizontal walking speeds (m/s)
(Stair-gradient: (degree))
Data of Fruin: Data of pedestrians aged more than 50 yrs old is applied into "Elderly"
Data of pedestrians aged from 30 to 50 yrs old is applied into "Young"

In our experiment, some people used the handrail when ascending/descending stairs, while others did not. Also, some younger participants passed a step especially when ascending in “fast mode.” Further analysis on effects of the handrail will appear elsewhere.

In conclusion, LEP showed a strong correlation with the walking speed on stairs among the elderly participants, as well as with the walking speed on a flat surface, and consequently LEP can be used to predict the walking speed for elderly people on stairs. Age, height, weight may be unnecessary variables to predict the walking speed. However the wide variation of LEP scores suggests that although it might be ignored when predicting walking speeds on stairs for younger people, it should be recorded individually for elderly people. Thus, our simulation model will need to be able to model individual participants explicitly in order to be able to investigate the effect of stairs on their walking ability and the effect of their presence in a group of people using a given flight of stairs. Based on the presented results, we are now developing an explicit pedestrian simulation model, which can represent a variety of pedestrians including elderly people. Prediction of the walking speed from the characteristics of pedestrians and demographic data will be presented in another paper.

5. Practical Application – About our simulation model-

The obtained knowledge and data will be used in our heterogeneous pedestrian simulation model. In this section, we provide a brief overview of our pedestrian simulation.

Our intention in developing a heterogeneous pedestrian simulation model is to evaluate accessibility in large public transport facilities, such as underground stations, by looking at the pedestrian flow. The results shown above indicate that we need to take account of the make-up of the pedestrian population. In particular, in an ageing society, we can expect more elderly people to use public transport. In the United Kingdom, the proportion of the people aged more than 65 was 16% in 1996 and in 2001, but will be 19% by 2021 and 25% by 2041 (Age concern, 1999). Similar increases are expected in most other countries in the world.

It is often supposed that elderly people walk slowly, but an important point is that each elderly person has his/her unique walking speed. The walking speed is determined by the capability of each person and characteristics of each facility (Cepolina and Tyler, 2003). A vertical gap would not be a big problem for healthy young people, but could be a mountainous challenge for vulnerable people. The poorer the design of facilities, the more people experience difficulty in using them. If many people encounter difficulty or if a small number of people within a group have a walking speed different from the average, the pedestrian flow and the capacity of the facility at peak time would be affected (Fujiyama, 2003). Our purpose in developing a pedestrian simulation model is to describe such a situation. In order to do this in our simulation, the walking speed of pedestrians will be determined by both characteristics of pedestrians and the facility. Fig.7 is a schematic representation for this notion.

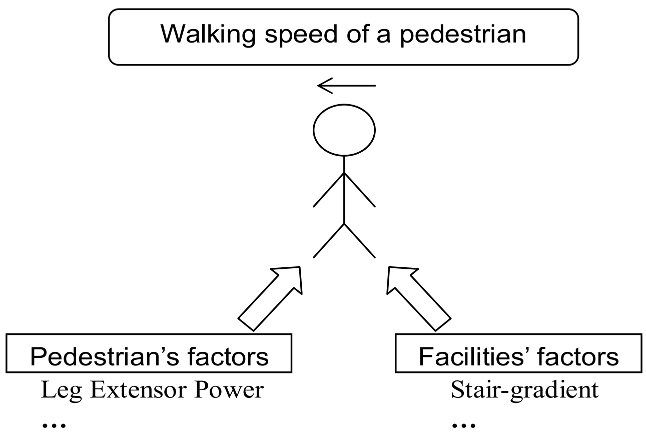

Fig 7. Schematic representation of the walking speed of each pedestrian

The empirical data will be used to generate a model which takes personal characteristics into account when predicting the walking speed of a pedestrian. In order to represent a variety of pedestrians according to the national population, the data will be used in conjunction with the Allied Dunbar National Fitness Survey (Sports Council, 1992), which investigated the physical indices used in our experiment and examined these (and other characteristics) across a large sample of the general population. The construction of this simulation model is the next stage of the research.

We hope that the application of the proposed simulation model will assist in the prediction of movements of individual pedestrians -especially elderly people- and how they interact with each other in the pedestrian environment. This is particularly relevant in the case of multi level facilities both those with lifts/stairs and those without them –hence the importance of this research.

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