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Bridging characteristics of a pedestrian and the facility the pedestrian uses: Prediction of the walking speed of a pedestrian on stairs

Abstract

In this paper we propose a framework in which the behaviour of a pedestrian is predicted based on the characteristics of both the pedestrian and the facility the pedestrian uses. As an example of its application, we developed a model to predict walking speeds of a pedestrian on stairs. We looked at the physiology and biomechanics of walking on stairs, and then developed a model that predicts a walking speed based on the weight and leg extensor power of the pedestrian, and the gradient of the stairs. The model was calibrated by our experiment and another study, and then validated by our observations and an existing study. The proposed framework establishes the importance of bridging the two types of characteristics: those of a pedestrian and those of the facility the pedestrian uses. Also, the developed walking speed model is useful for simulating how the design of stairs affects pedestrian circulation.

Key words: pedestrian simulation, walking speed, stairs, model, characteristics.

1. Introduction

Understanding the use of space by pedestrians is important for the design of buildings and stations. There have been a good number of studies on pedestrian traffic. They have been mainly observational or experimental studies, but since the1990s there has been much progress in the modelling of pedestrians. Benefiting from the rapid development of computer technology, many pedestrian simulations have been developed so that pedestrian behaviour can be simulated on the computer (e.g. Galea and Galparsoro, 1993; Helbing and Molnar, 1995; Kerridge and McNair, 1999). These simulations first achieved success in the representation of evacuation.

Recently, designers have begun to see pedestrian simulations as a tool for the design of buildings or stations, and to apply them to more common situations (Batty, 1997). For instance, designers would like to evaluate the resulting pedestrian circulation after the installation of a new facility, such as a café, in a railway station. Accordingly, it has been necessary to add more functions to pedestrian simulations so that pedestrian behaviour in a variety of situations can be simulated. A function by which each pedestrian in the simulation decides where to walk, for example, has been an important topic in the development of pedestrian simulations (e.g. Hoogendoorn and Bovy, 2002). Also, there have been studies that include existing theories and knowledge on the perception and psychology of pedestrians, which help simulations to represent pedestrians in the real world more accurately. One of these simulations is Turner and Penn (2002), which incorporated Gibson’s ecological theory of perception (Gibson, 1979). In their simulation, each pedestrian behaves according to his visual recognition of environments surrounding him. Another simulation is Rymill and Dodgson (2005), which integrated works on social relationships between pedestrians in the street by sociologists including Goffman (1972), Wolff (1973) and Collet and Marsh (1981). These undertakings show that pedestrian simulations can be a platform for theories and knowledge about pedestrians in other disciplines.

On the other hand, in order to run a pedestrian simulation properly, it is necessary for the simulation to have appropriate data regarding walking speeds, which are another important component of walking. There have been a good number of studies on walking speeds (Hankin and Wright, 1958; Older, 1968; Navin and Wheeler,1969; Virkler,1994; Young,1999), and recently researchers on pedestrian simulations started revisiting this important component (Seyfried et al., 2005; Teknomo and Gerilla, 2005). One of the important topics has been the capacity of the space and its relation to density and speed because these are important for the calculation of the necessary space to accommodate pedestrians. Fruin (1971) applied the notion of “Level of Service”, which was originally developed for vehicle traffic, to pedestrian traffic. At a later stage, the research focus was transferred to the pedestrian flow in various spaces. Daly et al. (1991) observed pedestrian flows in underground stations, whereas Cheung and Lam (1998) looked at route choice behaviour between escalator and stairs. Koshki (1988) looked at walking characteristics in a developing country. Some studies have looked at bottle necks (i.e. Daamen and Hoogendoorn, 2007; Kretz et al., 2006). Others look at counter flow (i.e. Isobe et al., 2004; Helbing et al., 2005; Lam et al., 2003). Also, there have been some studies on the extent to which ship motion affects walking speeds of passengers on board (e.g. Meyer-König et al., 2006).

There have also been studies concentrating on the effects of personal characteristics, such as age and gender, on walking speed (e.g. Wilson and Grayson, 1980; Bowman and Vecellio 1994). This knowledge is important because users of a building or a station are not homogeneous, and pedestrian simulations need to take account of differences in users. Tregenza (1976), which referred to Peschel (1957), showed that the average walking speed of children aged between 6 and 10 on a level surface was 1.1m/s; that of adolescents was 1.8m/s; that of men aged under 40 was 1.7m/s; that of men aged over 55 was 1.5m/s. Tregenza also stated that women tended to walk more slowly than men, showing that the average walking speed of women aged under 50 was 1.4m/s and that of elderly women was 1.3m/s. Because walking speeds of elderly people are an important factor for calculation of the signal timing of pedestrian crossings, this was also investigated by Coffin and Morrall (1995) and Knoblauch et al. (1996). Coffin and Morrall recommended 1.0m/s for design of crosswalks and intersections. Fruin (1971) obtained 1.4m/s for the average male walking speed and 1.3m/s for the female in his survey at bus and rail stations. These studies show that elderly people walk more slowly than young or middle–aged people and women's walking speeds are slower than those of men. In fact, differences in walking speeds according to age and gender have also been investigated by researchers in physiology. An experiment by Bendall et al. (1989) reported that the average walking speeds of their participants were 1.33m/s for men and 1.17m/s for women. Himann et al. (1988) showed that the walking speeds of their participants were similar as long as their ages were 62 or under. However, the speeds of the participants aged 63 or over declined according to age. The age-related decline in walking speeds has also been investigated by Voorbij and Steenbekkers (1998) and Bohannon (1997). These studies suggest that age and gender affect walking speeds.

In addition to studies on the effects of characteristics of pedestrians on walking speeds, there have also been studies on how walking speeds are affected by the characteristics of the facility pedestrians use. These studies are valuable because designers of buildings or stations are interested in how different designs (or characteristics) affect the pedestrian circulation in the building or station, and by integrating such knowledge into pedestrian simulations they can predict the effects. The effects of the dimensions of stairs on walking speeds are one topic that has been attracting researchers. Pauls (1980) investigated the walking speeds and density of pedestrians on stairs from the viewpoint of evacuation. He looked into the width of stairs and the capacity. The capacity of stairs was also studied by Fruin (1971) and Khisty (1985). Templer (1992) suggested an equation for the relationship between the walking speed on stairs and the characteristics of stairs, namely the riser-height and tread-depth. The equation was available for stairs with a tread-depth from 25.4 to 40.6cm and a riser-height from 12.7 to 17.8cm.

$$V_s = 23.47 + 0.253R - 0.305T \quad \cdots\cdots\cdots\cdots \text{(1)}$$

Where V_s: Vertical walking speed in metres per minute

T: Tread-depth in centimetres

R: Riser-height in centimetres

Graat et al. (1999), who conducted an experiment on two sets of stairs whose gradients are 30° and 38°, concluded that the steeper the slope of stairs, the slower people move on stars. Fruin (1971) conducted an observation on two sets of staircases. His results showed that average walking speeds on indoor stairs with a gradient of 32° were 0.51m/s for ascending and 0.67m/s for descending; those on outdoor stairs with 27° were 0.57m/s for ascending and 0.77m/s for descending. (Speeds here are in the horizontal direction.) He also categorised pedestrians into three age groups for both sexes, and showed that walking speed declined according to age and that women showed a lower value than men. Although details of the observation are not clear and the data may need to be investigated further, this work may be the only work that showed age-related differences in walking speeds of pedestrians on stairs. On the other hand, Sun et al. (1996) conducted an observation on walking speeds on ramps with different angles. One of their findings was that walking speeds of elderly pedestrians were more affected (became slower) by the gradient of ramp compared with those of younger pedestrians.

We have seen many existing studies suggesting that walking speeds of pedestrians are different according to gender and age. This may be reasonable because muscle strength and other physical capabilities of young and/or male pedestrians are higher than those of elderly and/or female pedestrians, and those with high muscle strength and physical capabilities can use more power for walking, thereby walking faster. Also, we have seen characteristics of a facility, such as dimensions of stairs, affect walking speeds. So, a question arises here: what is the interaction between the two types of characteristics: characteristics of pedestrians and those of the facilities pedestrians use? What is the process by which the human body decides a walking speed? Indeed, most walking studies have treated personal characteristics and the facility's characteristics separately, and no model has been proposed to bridge them. For instance, a pedestrian who is not physically strong (e.g. an elderly pedestrian) would walk more slowly on stairs than young pedestrians. If the gradient of the stairs is steep, the pedestrian would walk even more slowly. If we have a model that predicts the walking speed based on both characteristics of a pedestrian and the facility the pedestrian uses, the model can represent such situations as elderly pedestrians walking very slowly on steep stairs. Figure 1 is a schematic representation of the model. One of the benefits of having such a model is that, by integrating it into a pedestrian simulation, we can predict how different designs (for example, the stair-gradient) affect a pedestrian or pedestrians with a certain profile.

Insert figure 1 here

Therefore, we set the objectives of this paper as 1) to propose a framework in which both characteristics of a pedestrian and characteristics of the facility the pedestrian uses are taken into account; and 2) to develop a model for walking speeds based on the proposed framework. It should be noted that in this paper, we particularly consider walking speeds of pedestrians on stairs. This is because stairs are a necessary component of buildings, stations and terminals, and when a simulation needs to represent a whole building or station, stairs should be included. Also, in walking speeds on stairs, interactions between characteristics of a pedestrian and the facility the pedestrian uses would be evident. In the following sections, this paper first proposes a framework. Then, we look into the physiology and biomechanics of walking, and develop a walking speed model based on the framework. The model is calibrated by our empirical data and also data of a previous study, followed by validation by the results of our observations as well as those of another study.

2. Framework for bridging the characteristics of a pedestrian and the facility the pedestrian uses

There have been very few studies on a model or a framework on pedestrian behaviour that considers interaction between characteristics of pedestrians and the facility the pedestrians use. We identified only one paper, which is Cepolina and Tyler (2004). Cepolina and Tyler proposed a framework in which characteristics of both a pedestrian and environments decide the resulting behaviour of the pedestrian. In their framework, when a pedestrian tries to use a facility, the capabilities of the pedestrian are compared to the capabilities required by the facility. If the required capabilities exceed the capabilities of the pedestrian, he cannot proceed, and thus avoids the facility. For example, when a pedestrian encounters a vertical gap on the ground, if his capability (maximum climbable height) exceeds the required capability (the height of the gap), he proceeds and goes over the gap. If it does not, the pedestrian avoids the gap and changes his walking direction. According to Cepolina and Tyler, outputs of this capability comparison are discrete: a pedestrian proceeds or avoids.

This paper takes a different approach. We propose a new framework in which the output can vary according to the difference between the required capabilities and the provided capabilities. If a person confronts a facility, the less the requirement of the facility, the more easily the person can manage it. The output can be a continuous value, such as the walking speed. When, for example, a pedestrian goes over a vertical gap, if his capability (i.e. maximum climbable height) is much higher than the capability required by the environment (i.e. the height of the gap), he can quickly go over it.

Figure 2 is a schematic representation of how the proposed framework works. Here we take “going over a step” as an example. X-axis of the figure represents *Requirement of the facility* (in this example, step height), and Y-axis means the output (in this example, walking speed). The figure shows that the lower the requirement (step height), the faster a pedestrian can go over the step. Each pedestrian has a unique curve for the relationship between the requirement of the facility (step height) and the output (walking speed) according to the capabilities of the pedestrian. A physically strong pedestrian could go over the same height faster than others with less physical capability. Each pedestrian has a different “requirement of the facility – output” curve for each action (e.g. going over a step, walking on an upward slope, etc). The shape of the curve needs to be identified for each action, but some actions may have a cut-off (for example, in the case of going over a step, the pedestrian cannot go over a step whose height is greater than his maximum climbable height). For the details of the framework, please see Fujiyama (2004). In the following sections, we develop a model for walking speeds on stairs based on this framework. In the next section, we first look into biomechanics of walking and develop a model for walking speeds on stairs.

Insert figure 2 here

3. Biomechanics and physiology of walking speeds

In this section, we develop a model that incorporates the process of deciding the walking speed based on both the characteristics of a pedestrian and the characteristics of the facility the pedestrian uses. We first look into biomechanics and physiology of walking, and then develop the model.

In order to develop a model for human movements, it is necessary to understand the musculoskeletal system of the human body. Walking involves action of all the body segments in a highly coordinated manner. The forces that cause this movement are a combination of muscle activities to accelerate or decelerate the body segments and the effects of gravity and momentum. In stair climbing, substantial forces are involved because of the need to transpose the centre of gravity vertically (Trew, 2005). However, it is the lower limb that plays the main role in walking.

When modelling the mechanism of the human body, it is necessary to consider what level of detail is required. There have been some studies that model the whole human musculoskeletal system. Casburn et al. (2007) is an example of this approach. In fact, several computer simulations of the musculoskeletal system have been developed in biomechanics and medicine. They have been used in the analysis of the contribution of specific muscles to the performance of certain motions, as well as in diagnosis and scheduling for rehabilitation (Hase and

Yamazaki, 2002). Examples of such simulations are Delp and Loan (1995) and Komura et al. (2005).

However, a model that includes the whole musculoskeletal system of the human body requires a huge computation. Our aim is to develop a model that predicts walking speeds, which is just one scalar value and will be used in a pedestrian simulation for stations and buildings. Consequently we need to simulate not only one human body but many pedestrians. It is therefore not practical to have a model with considerable detail of the human body. This is also the case regarding the characteristics of the facility. There may be many factors of the facility that affect walking speeds, but inclusion of a large number of factors could lead to a cumbersome computation. The model we develop should be simple but robust enough to predict walking speeds.

There has been physiological research on the strength of lower limbs and walking speeds. Strength of legs has been found to be associated with functional limitations, such as walking speed (Rantanen, 2003). Bassey (1997) stated that the power (strength$\times$speed) is the most functionally relevant measure of the weight-bearing muscles since it is power rather than strength which is used in locomotion. Indeed, research has shown that the leg extensor power (LEP) shows a high correlation with walking speeds (i.e. Mockett et al.1996; Bean et al. 2002). Bassey et al. (1992) also examined the relationship between LEP and the stair climbing speed of elderly people. His study showed that the correlation coefficient between the stair climbing speed and LEP/weight (LEP divided by weight) was 0.81. The result is reasonable because the muscles of the lower limbs need to create substantial forces in order to lift up the body mass, and thus the extensor power of a lower limb and walking speeds show a very high correlation physiologically speaking. In the next section, using leg extensor power as a variable, we develop a model to predict walking speeds.

4. Modelling the mechanism of walking speeds

This section develops a model to predict walking speeds. Here, we consider a mechanically-based model because moving the body mass in a vertical direction is a significant action and leg extensor power is related to walking speeds on stairs. Indeed, Benedict and Parmenter (1928) suggest that when a pedestrian ascends one meter, the total metabolism is approximately 10 to 13 times greater than when he walks one meter horizontally. This implies that vertical movement of the human body requires much more energy than horizontal movement. It should be noted that existing studies also suggest that there are other characteristics that affect walking speeds. For example, crowd density also may affect walking speeds. However, this study focuses on free speed, which is defined as the speed at which the pedestrian wants to walk when not obstructed by other pedestrians.

The energy of an object is defined as below.

$$E = m \cdot g \cdot h + \frac{1}{2} m \cdot v^2 \quad \cdots\cdots\cdots \text{(2)}$$

where

E: Energy (j)

m: weight (kg)

g: gravity coefficient

h: vertical position (m)

v: velocity (m/s)

To divide the velocity into the horizontal and vertical component.

$$E = m \cdot g \cdot h + \frac{1}{2} m \cdot \left(v_v^2 + v_h^2\right) \quad \cdots\cdots\cdots\cdot (3)$$

where v_v: velocity (vertical component) (m/s)

v_h: velocity (horizontal component) (m/s)

As $\tan\theta = \frac{v_v}{v_h}$ (see figure 3), equation 3 can be transformed to

$$E = m \cdot g \cdot h + \frac{1}{2} m \cdot v_v^2 \cdot (1 + \frac{1}{\tan^2\theta}) \quad \cdots\cdots\cdots\cdot (4)$$

insert figure 3 here

Differentiate equation 2 by time

$$\frac{d}{dt} E = m \cdot g \cdot \frac{d}{dt} h + \frac{1}{2} m \cdot (1 + \frac{1}{\tan^2\theta}) \cdot \frac{d}{dt} v_v^2 \quad \cdots\cdots\cdots\cdot (5)$$

As $\frac{d}{dt} h = v_v$ and $\frac{d}{dt} E = P$ where *P*: power (Watt), equation 5 can be

$$P = m \cdot g \cdot v_v + m \cdot (1 + \frac{1}{\tan^2\theta}) \cdot v_v \cdot \frac{d}{dt} v_v \quad \cdots\cdots\cdots\cdot (6)$$

We suppose $\frac{d}{dt}v_v = 0$, which means that the velocity is constant. Equation 6 becomes

$$P = m \cdot g \cdot v_v \cdots\cdots\cdots \text{(7)}$$

As $\tan\theta = \frac{v_v}{v_h}$, equation 7 becomes

$$v_h = \frac{P}{m \cdot g \cdot \tan\theta} \cdots\cdots\cdots \text{(8)}$$

As P, m and tan θ are different variables, it would be better to treat them separately as

$$v_h = \alpha_0 + \alpha_1 \cdot P + \alpha_2 \cdot m + \alpha_3 \cdot \tan\theta \cdots\cdots\cdots \text{(9)}$$

where α_0, α_1, α_2, α_3: coefficient

Equation 9 suggests that the power and weight of a person and the tangent value of the stair-gradient could influence the horizontal walking speed of the person on stairs.

As we have seen in the previous section, although stair walking involves movements of the whole body, the lower limb is the main factor. Therefore, we use the leg extensor power for P in equation 9 in the calibration of the model. Although it is not in the equation, body size might affect walking speeds. Thus, we also consider a model that includes the height of the person for comparison. Moreover, it is also possible that if pedestrians walk on stairs for a long time, for example climbing up more than two stories, fatigue may affect walking speeds. However, as the scope of this research is to investigate the mechanism of walking speeds that bridges the characteristics of a pedestrian and the characteristics of the facility the pedestrian uses, we shall not take account of fatigue in the model.

There may be other characteristics of the facility in addition to the stair-gradient that affect walking speed. For example, the availability of a handrail, from which the pedestrian could obtain a reactive force to lift up or to support the body mass. However, for simplification, we shall not consider characteristics other than stair dimensions (the riser-height and tread-depth), which have been investigated by many researchers especially from the viewpoint of safety (e.g. Irvine et al.1990; Kose et al.1985). The model calibration will also consider a model that uses the riser-height and the tread-depth for comparison.

It has been suggested by Young (1986) and Buchner et al.(1996) that there is a threshold for the relationship between the strength (power) and the functional ability. According to this threshold model, walking speed corresponds to the leg extensor power until a certain point, but above this point a further increase of power does not necessarily improve the walking speed. Figure 4 is a schematic representation of this model. In order to take account of this non-linearity, it would be appropriate to use a log curve. On this basis, we modify equation 9 as

$$v_h = \alpha_0 + \alpha_1 \cdot l_n(P) + \alpha_2 \cdot m + \alpha_3 \cdot \tan\theta \cdots\cdots\cdots \text{(10)}$$

Insert figure 4 here

In the following sections, we calibrate and validate the model we developed.

5. Experiment

In this section, we briefly describe the experiment we conducted, the results of which will be used to calibrate our walking speed model. The experiment was conducted using four staircases with different gradients in a university campus. Here we show a summary of the experiment. Details of the experiment were shown elsewhere (Fujiyama and Tyler, 2004).

The experiment was conducted to investigate the relationships between the characteristics of a pedestrian and the characteristics of the facility the pedestrian uses. Since eventually we want to predict walking speeds of various people, we also considered extrapolation of the results when planning the experiments. The survey data that will be used for the extrapolation is Allied Dunbar National Fitness Survey Data (ADNFSD), which is a physiological survey at a national level across England with 1,986 participants (Sports Council and Health Education Authority, 1992).

In the experiment, we asked each participant to ascend and descend a flight of each staircase at his/her normal walking speed and at his/her fast walking speed, which means that we measured four speeds for each participant, namely the normal ascending speed, the normal descending speed, the fast ascending speed and the fast descending speed. Because in real situations some people run on stairs when hurrying and we wanted to predict the running speeds as well, we measured fast walking speeds in the experiment, which will be used to predict running speeds. Each participant was asked to repeat this exercise on four staircases with different stair-gradients.

The experiment included participants divided into two groups: one consisted of people aged 60 or over; the other consisted mainly of university students. There were 18 participants in the elderly group and 15 in the young and middle-age group. One reason for having two groups was to make sure the experiment covers the whole population. Another reason was that it was logistically impossible to test all the participants at once. We also measured characteristics of each participant: the weight, the height and the leg extensor power (LEP). LEP was measured using a leg power rig, which consisted of a seat and a footplate connected through a lever and chain to a flywheel. For more information about the leg power rig, including its reliability, the authors refer to Bassey and Short (1990). Participants were asked to sit on the seat and tread on the footplate as fast and as strongly as possible. A device attached to the flywheel calculated the leg extensor power. The measurement procedure of LEP was in line with Bassey and Short (1990). Figure 5 shows the leg power rig.

insert figure 5 here

Figure 6 shows the relationship between walking speeds and leg extensor power on staircases. From figure 6 it is not clear whether the relationship between LEP and horizontal walking speeds is log-linear. Figure 7 shows the linear relationship between stair-gradients and the average ascending speeds of the study groups.

Note that a summary of the experiment results is shown at the end of this paper (table VIII).

insert figure 6 here

insert figure 7 here

The results of the experiment were largely in line with the equation 10. However, from figure 6 the relationship between LEP and horizontal walking speeds is not clear. It might be better to use a linear curve rather than a log-linear curve. For this reason, we will test both log value and original value of LEP in the calibration.

6 Model calibration

6-1. Calibration 1

In this section, we calibrate the proposed walking speed model. First, using the data of the experiment, we compare several extensions of the model. Then, we further calibrate the selected model.

Equation 10 is a regression model with variables of the log value of LEP, the weight and the stair-gradient (Model 1). However, the results of our experiment did not show a clear relationship between the log value of LEP and walking speeds, and therefore we here consider a model that uses original values of LEP (Model 2).

Also, for comparison, we test a model that uses the riser-height and the tread-depth instead of the stair-gradient (Model 3) because some previous models, such as Templer (1992), used these characteristics. Moreover, we consider a model that includes the height because this may also affect walking speeds (Model 4).

Model 1: $v_h = \alpha_0 + \alpha_1 \cdot l_n(P) + \alpha_2 \cdot m + \alpha_3 \cdot \tan\theta$

Model 2: $v_h = \alpha_0 + \alpha_1 \cdot P + \alpha_2 \cdot m + \alpha_3 \cdot \tan\theta$

Model 3: $v_h = \alpha_0 + \alpha_1 \cdot P + \alpha_2 \cdot m + \alpha_3 \cdot R + \alpha_4 \cdot T$

Model 4: $v_h = \alpha_0 + \alpha_1 \cdot P + \alpha_2 \cdot m + \alpha_3 \cdot \tan\theta + \alpha_4 \cdot H$

where v_h: velocity (horizontal component) (m/s)

m: weight (of the participant)(kg)

P: LEP (leg extensor power) (Watt)

θ: stair-gradient (deg)

R: riser-height (m)

T: tread-depth (m)

T: height (of the person) (m)

$\alpha_0, \alpha_1, \alpha_2, \alpha_3, \alpha_4$: coefficient

Using the data of the experiment described in the last section, we compute coefficients, as well as a multiple R value and an F value, for each model. As we have four type of walking speeds (normal ascending, normal descending, fast ascending, fast descending), we calculate coefficients for each type of walking speed. Note that we call a model for each type a “sub-model”. In the computation, because we want to exclude cultural influence on walking speed and eventually link the model to ADNFSD, we exclude those who are from a non-European country and have been in the UK for less than two years. In total, 28 participants' data are used for the model development.

Firstly, we compare coefficients of each sub-model for Model 1, 2, 3 and 4, and then look at details of the proposed model. Table I shows multiple R and F values of the models. Comparison between Model 1 and Model 2 in table I leads us to notice that Model 1, which uses log values of LEP rather than original values, is better in the prediction of walking speeds in all the four sub-models. Also, multiple R results of Model 3 indicate almost no difference in the prediction compared with Model 1. This is also the case for Model 4. In regression analysis, having more variables leads to a better multiple R. Because we want to keep the model simple and there is not a big difference in multiple R, we use Model 1 for later analysis.

insert table I here

Table II shows coefficients and t values of Model 1. Comparison of the t values in Model 1 in table I leads us to notice that the LEP value and the tangent value of stair-gradients are useful in predicting the walking speeds. This implies that the LEP and the stair-gradient are important characteristics in determining walking speeds. Also, table I shows that results for descending show higher correlation than those for ascending. While descending, quadriceps musculature is necessary to absorb forces and to decelerate the increasing load as the weight-bearing limb is stabilised beneath the load (Sowers et al., 2006), and also joint torques in descending are larger than those in ascending (Salsich et al., 2001). These studies imply that descending requires more muscle strength to keep the body stable.

Because there is a high correlation between muscle strength and LEP (Bean et al., 2002), the sub models for descending may show a higher correlation than those for ascending.

insert table II here

6-2. Calibration 2

We have found coefficients for our walking speed model, but it may be necessary to modify the model further in order to apply it to real situations. This is because the walking speeds calculated in our walking speed model may be higher (faster) than observed walking speeds for the following reasons:

1) In the experiment on which our model is based, the participants walked with some concentration even though they were asked to walk as they do in real situations. In real situations of walking on stairs, some pedestrians may not concentrate on walking so much, for example, some may be concentrating on listening to music using a portable player.
2) In the experiment, the participants wore comfortable shoes and clothes for walking, whereas on actual stairs some wear tight trousers, high heels, boots, etc, which may reduce walking speeds.

To begin with, we assume that pedestrians on stairs use the normal walking speed for ascending and descending stairs. Therefore, for calibration, we use our sub-model for the normal ascending speed and the normal descending speed. The outputs of the linear regression model can be modified as

$V_h = \alpha \cdot V_{hc}$ ·········· (11)

where V_h: Predicted (horizontal) walking speed

α: Modification coefficient

V_{hc}: Horizontal walking speed calculated based on our experiment

In order to calculate α, we compare the walking speeds calculated by our model with the results of the observations of ascending pedestrians by Fruin (1971), who measured walking speeds on two sets of stairs, namely indoor stairs with a 32 degree gradient and outdoor stairs with a 27 degree gradient.

For the input values of the regression model, namely LEP and weight, we use the values calculated from the results of ADNFSD. It should be noted that Fruin's observations took place in railway stations. Because details about the observations were not well described, we assume that the observed pedestrians were representative of average pedestrians, and walked at their free speed. Also, the railway stations were in the United States, and there might be some difference in the LEP and weight values between the English and US populations. Unfortunately, there were no available LEP data for the US population with a large sample size partly because LEP was invented in the United Kingdom and began to be used from the1990s (Bassey and Short, 1990). As Caucasians are thought to be a large proportion in both samples, we use the LEP values in ADNFSD for this calibration. In fact, Daamen and Hoogendoorn (2007) pointed out the similarity of walking speeds between North America and Europe. We calculate the average of men's and women's LEP values from the survey data. For the weight value, we use the result of NHANES I (National Health and Nutrition Examination Survey) conducted in the United States in 1971-74 (Ogden et al. 2004). All the values input in the model are shown in tables 10 and 11 at the end of this paper.

The comparison suggests that if we multiply the walking speeds of our model by 0.721, the multiplied values are similar to Fruin's observation results. Therefore, we set α in equation 11 as 0.721. Table III shows this calibration.

insert table III here

7. Validation

7-1. Introduction

One possible way to validate the model is to conduct another experiment. However, in this case, the measured walking speeds would be walking speeds recorded in an experiment, which may be different from those in real situations. Because our intention is to predict walking speeds in real situations, we need to test the model by comparing walking speeds calculated by our model with those observed in real situations. On the other hand, it is practically impossible to measure the LEP of each pedestrian observed in a real situation. Nevertheless, it would be possible to predict an average walking speed of a group with a good number of people given that we already know the profile of the group and thus can predict an average LEP and weight. Therefore, for validation we compare walking speeds calculated by our model with three sets of data including different profiles of pedestrians.

We first compare the walking speeds calculated by our model with the results of Templer's (1991) model, which was based on his observations. Then, we compare our model's results with two sets of our own observation results, where profiles of the group and stair-gradients are different. We use the average LEP and weight predicted from the profile of the group observed. We also compute the standard deviation of the observed speeds from the predicted walking speeds. If the model is good and the group is well specified, which means that components of the group have a similar LEP, the standard deviation would be small.

7-2. Comparison with Templer's (1991) model

Templer suggested a model to predict walking speeds based on his observations (equation 1). Templer did not give details of the observations, and thus we assume that his model considered average values of observed walking speeds of people. Therefore, the input weight value is an average value from NHANES III conducted in 1988-94 (Ogden et al., 2004). For input LEP values, because LEP data about North American people are not available, we used the average value calculated from ADNFSD for the same reason as in Calibration 2. It should be noted that input values for Templer's model are the riser-height and the tread-depth, so that there can be several sets of stairs whose riser-heights and tread-depths are different but whose stair-gradients are the same. On the other hand, our model's input value for the characteristics of stairs is the stair-gradient. In order to compare our model and Templer's model, we input into Templer's model the dimensions of the four stairs used in our experiment and compare the outputs of both Templer's model and our model. (For details, please see table X at the end of this paper.)

Table IV shows that the values of the two models are close to each other in all stairs except Stair 1. However, Stair 1 is outside the range of sizes of stairs to which Templer's model can be applied. Also, according to UK Building regulations, it is impossible to build stairs with the same dimension as Staircase 1 because they would be too steep (Office of the Deputy Prime Minister, 2006). It may therefore be reasonable to ignore the output of Templer's model for Staircase 1. Thus, we could conclude that the walking speeds of our model and Templer's model are similar.

insert table IV here

7-3. Validation observation 1

The first observation was performed at a staircase with the stair-gradient of 27.3° in a London Underground station. The dimensions of the stairs are in table X at the end of the paper. The staircase is a dog-leg staircase consisting of two flights and a middle-landing, and links the ground level and the concourse level. The observed flight was the one connected to the concourse level.

The observation was conducted in the morning after peak travelling time on a weekday. The observed people were aged 65 or more. During the observation, an observer stood on the lower landing, noted single elderly pedestrians, measured the time taken by them to ascend the flight of stairs, and wrote down the time as well as their predicted age and their gender. The observer stood on the floor connected to the lower landing, and his standing position was far enough not to obstruct the observed pedestrian but near enough to observe him. The selection of observed pedestrians was based on the first-comer first-observed principle, in which the observer chose the next single elderly pedestrian spotted after completing the observation on the previous one. When two or more pedestrians were present on the stairs, observation was not conducted or was stopped because if another pedestrian was already on the stairs or on the landing, his presence might affect the walking speed of the focused pedestrian. Also, we excluded pedestrians carrying large luggage. Our definition of “having large luggage” was having luggage in both hands or having luggage with wheels (i.e. a suitcase). The predict of the pedestrians’ age was done by the observer based on their appearance. We did not test the reliability of the predicts, but the observer was working on elderly people’s transport problems for a long time, and has appropriate experience to make a valid judgement. The observer measured, by a stopwatch, the time between the moment when the pedestrian trod on the first stair of the flight and the moment when the pedestrian trod on the last stair. In total, 57 elderly pedestrians were observed with 19 ascending males, 11 ascending females, 18 descending males and 9 descending females.

For the prediction of walking speeds using our model, the input value for characteristics of pedestrians is the average LEP value of people aged 65 or over. Because ADNFSD does not include elderly samples aged 75 or over, we used the LEP values measured by Skelton et al. (1994). Regarding the input weight values, we calculated an average weight of people aged 65 or over based on Health Survey for England 2004 (Health and Social Care Information Centre, 2005).

Table V shows the comparison between the walking speeds computed by our model and the average walking speeds of the pedestrians observed. Standard deviation values in the table are the deviations of the observed speeds from the walking speeds of our model. Table V shows that for ascending speeds, the model has a 10% error but for descending speeds the walking speeds of our model are close to the walking speeds of the pedestrians observed.

insert table V here

7-4. Validation observation 2

The second observation was performed at a staircase with the stair-gradient of 30.5° in a university campus in London. The dimensions of the stairs are in table X. The staircase is a dog-leg staircase consisting of two flights and a middle-landing, and connects the ground floor and the first floor. The observed flight is next to the ground floor.

The observation was conducted in the afternoon of a weekday in term-time. The observed people were aged 16 to 35. For the data recording, we used spy cameras connected to a digital camcorder. The cameras are very small and it was difficult to spot a camera or to notice that the recording was being conducted. From the video, we chose pedestrians who looked age 16 to 35. Again, we only chose single pedestrians in the situation where there was no other pedestrian on the stairs or on the landings before and while walking on the stairs. We measured the time between the moment when the pedestrian trod on the first stair of the flight and the moment when the pedestrian trod on the last stair. In total, 109 pedestrians were chosen for the analysis: 36 ascending males, 27 ascending females, 31 descending males and 13 descending females. It is assumed that they were mainly university students.

For the prediction of walking speeds using our model, the input values are the average LEP and weight of people aged 16 to 35. Weight values are again extracted from the average values in England for 2004 and LEP values are from ADNFSD.

Table VI shows the comparison between the walking speeds of our model and the average walking speeds of the pedestrians observed. Table VI shows that in the case of walking speeds of male pedestrians, there is a large difference between the walking speeds of our model and the average values of the walking speeds of the observed pedestrians. This may be because some male pedestrians “ran” on the stairs whereas the model assumes that all pedestrians ascend or descend stairs at the normal walking speed, and therefore the observed values are faster than the model’s walking speeds. On the other hand, the proportion of the female pedestrians who ran on the stairs to the total female pedestrians was comparatively small. Thus, the comparison with observed male pedestrians produced a larger difference than observed female pedestrians.

insert table VI here

Concerning the speeds of those who ran on stairs, we calculated the average values of those who were regarded as running. Our definition of “running” was that, when ascending, pedestrians who “skipped” a stair (those who did not step on every stair) were regarded as “running”. For descending, as there is no clear definition, the observer judged whether the pedestrian ran or not based on the observer’s perception. Regarded as running were 22 ascending males, 18 descending males and 2 descending females (but no ascending females). We also computed walking speeds of our model for fast ascending and descending speeds. Table VII compares both values.

insert table VII here

Table VII suggests that for ascending, there is still a 16% difference between the computed walking speed and the observed walking speed, whereas for descending the model’s walking speed has a 7% difference from the observed value. In fact, it was observed that some male pedestrians were literally rushing up the stairs to a classroom just before the starting time of lectures. This might have affected the observation result. Also, walking speeds for running down stairs may vary according to personal preference, whereas comfortably skipping a stair with each step (or comfortably stepping on every two stairs) requires at least a certain speed. This could explain why the standard deviance for descending is larger than the one for ascending.

8. Discussion

8-1.Framework

This paper presented a framework to bridge characteristics of a pedestrian and the facility the pedestrian uses. Based on the proposed framework, we developed a model that predicts walking speeds on stairs.

There have been many studies on walking speeds. Some looked at how a pedestrian's characteristics, such as age and gender, affect the walking speed, whereas others looked at characteristics of the facility the pedestrian uses, such as the dimensions of stairs. Yet, few studies take account of both types of characteristics. The proposed framework is an attempt to bridge the two types of characteristics. It is useful to have models that explain interactions between the characteristics of a pedestrian and the possible design of the facility (stairs) and to predict the resulting behaviour of the pedestrian. (In this study's case, the resulting behaviour is the walking speed). Such models can be integrated into pedestrian simulations, which are used to evaluate designs of buildings and stations.

The presented research focused on walking speeds on stairs. There are other issues that can be considered using the proposed framework in order to evaluate designs of buildings and stations. For example, the sizes of letters on signs or information boards in a station and visual capabilities of pedestrians (e.g. visual acuity) could be modelled. Such a model is valuable when simulating pedestrian circulation in a station because pedestrians need to stop to see information about the train they want to take, and the location of unmoving pedestrians would certainly affect pedestrian circulation in the station. Developments of such models will make pedestrian simulation more powerful and useful.

8-2. Development of our walking speed model

The results of the validation suggest that our walking speed model is generally capable of predicting walking speeds of pedestrians on stairs who walk at the normal speed. However, some pedestrians, especially young male pedestrians, run on stairs. Our fast walking speed could be applied to young male descending pedestrians, but the model has more than a 10% difference for young male ascending pedestrians. It is speculated that the running speed on stairs is more influenced by the intention of pedestrians than the normal walking speed. The more they are hurrying, the faster the pedestrian may run. Because our walking speed model excludes such a personal intention factor, the model could not predict accurately running speeds. Interestingly, there has been little research on running speeds of pedestrians. It would be interesting to investigate this. Also, it was observed that some descending running pedestrians hold a handrail to keep their balance by obtaining a reactive force from the handrail. This may be another reason why our model cannot predict walking speeds of young descending pedestrians who run. (Although the rate is 93%, the standard deviation is more than 0.4).

Our walking speed model is based on mechanics and only includes the stair-gradient, LEP and weight as variables. Some existing studies suggest that the tread-depth and the riser-height as well as physical properties, such as body size, influence the walking speed. The results of our regression analysis showed that the inclusion of such variables did not largely improve the prediction. However, it is imagined that comprehensive inclusion of more personal factors and other characteristics of the facility, such as the motivation of the pedestrian and the availability of a handrail, would help predict walking speeds more accurately. Because we wanted to keep our walking speed model simple, we did not integrate many characteristics into our model.

8-3. Application of the model

Figures 8 and 9 show the relationships between stair-gradients and ascending and descending walking speeds calculated by our model. LEP values used are from ADNFSD. For the weight value, the average values of English population (Health and Social Care Information Centre, 2005) are used. The dashed lines in figure 8 show the walking speeds calculated by Templer's model (equation 1). It should be noted that his model predicts vertical walking speeds, which are converted to horizontal walking speeds by the authors. As inputs of his model are the tread-depth and the riser-height, there are several possible dimensions of stairs with the same stair-gradient. The lines in the figure show the lowest and highest possible walking speeds as per the limits for the inputs set by Templer. Interestingly, in both figures, the average speeds are closer to those of young people than elderly people. This result corresponds with Himann et al. (1988), in which the participants aged 62 or under on a level surface show similar walking speeds whereas walking speeds of those aged 63 or over decrease according to age, which leads us to infer that the average walking speed of a population may be closer to that of young people than that of elderly people.

insert figure 8 here

insert figure 9 here

The walking speed model presented in this paper is useful for the design of large buildings or stations because walking speed is one of the most important elements in the design. The model shows that walking speeds of pedestrians on stairs with different gradients are not the same, which is often forgotten. Designers should use a walking speed on stairs that pertains to the stair-gradient. Also, the presented model shows that different people have different walking speeds. Another application of the model is the prediction of walking speeds of people with a specific profile. In the design of a building or facility where the demographic profiles of users are different, for example where the proportion of female or elderly users is large, it would not be appropriate to use the average walking speed of the population. Our model can consider differences among pedestrians and should be used in such cases.

Daamen and Hoorgendoorn (2007) mentioned the influence of culture on walking speeds. It is reasonable to guess that models for walking speeds of pedestrians for different countries show different coefficient values. Using the methods presented in this study, a model to predict walking speeds for a population can be developed for any population, and comparison of coefficients between such models and our model would be interesting. In some countries the leg strength information is more common than LEP data, and thus LEP data at a national level does not exist. The variables of the model should be modified and tested taking into consideration the availability of such national physiological or epidemiological survey data and statistics.

It should be noted that we used an old American data set in the calibration and validation of the model because data about walking stairs are scarce. On the other hand, we also used English physiological data in 1990's, whereas our experiment took place in 2003. Although Daamen and Hoorgendoorn (2007) suggested the similarity of walking speeds between Europe and North America, there is a possibility that the state of health of people has changed over time, which might have affected the calibration and validation of our model. In fact, it was reported in a recent conference that the number of obese people recently increased and this could affect walking speeds of a crowd of pedestrians (PED 2008). Although our validation results proved that the proposed model can reasonably predict walking speeds of pedestrians, a further collection of walking speed data of pedestrians on stairs as well as a new physiological survey could contribute to more accurate prediction of walking speeds.

Furthermore, because our research is preliminary research to develop a model that bridges personal and environmental characteristics, we had only 28 participants in the experiment. Although the model obtained relatively good validation results, another experiment would be necessary to intensively use our walking speed model for more accurate prediction.

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11. Authors Note:

1) A summary of the results of the experiment (figure 6 and 7) is below.

insert table VIII here

2) Input values for our models for figure 8 and 9 are in table IX and X.

insert table IX here

insert table X here

Tables and figures

Table I. Comparison of multiple R and F values between Models

		SubModel for			
		Normal Ascending	Normal Descending	Fast Ascending	Fast Descending
Model 1 Base model	Multiple R	0.738	0.769	0.806	0.841
	F	43.1	52.2	66.3	86.5
Model 2 Non-log LEP	Multiple R	0.726	0.719	0.801	0.808
	F	40.1	38.5	63.8	67.2
Model 3 Tread-depth, Riser-height	Multiple R	0.740	0.770	0.810	0.843
	F	32.4	39.0	50.4	64.9
Model 4 inc height	Multiple R	0.744	0.783	0.809	0.843
	F	33.1	42.4	50.1	65.0

Table II. Coefficients and t value of Model 1

		Sub model for			
		Normal Ascending	Normal Descending	Fast Ascending	Fast Descending
Multiple r		0.738	0.769	0.806	0.841
F		43.1	52.2	66.3	86.5
Coefficients	Intercept	0.795	0.911	0.718	0.754
	weight(kg)	-0.00044	-0.00334	-0.00055	-0.00110
	Tan*	-0.82	-0.88	-1.15	-1.08
	Log(LEP)	0.083	0.127	0.213	0.207
t-value	Intercept	8.47	8.64	5.02	6.32
	weight(kg)	-0.46	-3.11	-0.38	-0.91
	Tan*	-9.34	-8.91	-8.66	-9.71
	Log(LEP)	6.39	8.72	10.86	12.62

Tan*: Tangent value of the stair gradient

Table III. Calibration of the model

		Fruin A	Fruin B
Stair-gradient	deg	32.0	27.0
Output of our model (V_{hc})	m/s	0.701	0.796
Fruin's observation result	m/s	0.510	0.570
Modified values of our model (V_h)	m/s	0.505	0.574

Note: $V_h = V_{hc} \times 0.721$

Table IV. Comparison of outputs between our model and Templer’s model

Staircase	deg	Our model (A)	Templer's model (B)	Rate (A / B)
Staircase 1	38.8	0.397	0.438	91%
Staircase 2	35.0	0.459	0.483	95%
Staircase 3	30.5	0.526	0.547	96%
Staircase 4	24.6	0.603	0.626	96%

Unit: m/s

Table V. Comparison of the walking speeds calculated by our model with observed speeds of elderly pedestrians

		Model output (A)	Observed (average) (B)	Rate (A / B)	Standard deviation
Ascending	Male	0.541	0.601	90%	0.294
	Female	0.511	0.475	108%	0.126
Descending	Male	0.592	0.596	99%	0.088
	Female	0.571	0.565	101%	0.097

Unit: m/s

Table VI. Comparison of the walking speeds calculated by our model with observed speeds of young pedestrians

		Model output (A)	Observed (average) (B)	Rate (A / B)	Standard deviation
Ascending	Male	0.551	0.668	83%	0.200
	Female	0.521	0.511	102%	0.052
Descending	Male	0.630	0.811	78%	0.323
	Female	0.608	0.631	96%	0.119

Unit: m/s

Table VII. Comparison of the walking speeds calculated by our model with observed speeds of young male pedestrians who ran on stairs

	Model output (A)	Observed (average) (B)	Rate (A / B)	Standard deviation
Ascending	0.899	0.773	116%	0.250
Descending	0.898	0.967	93%	0.415

Unit: m/s

Table VIII. Summary of experiment results

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	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	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	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	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. unit: (m/s)

Significance of difference tested using unpaired *t* tests.

NS = not significant

Table IX. Input characteristics of pedestrians

		Weight (kg)	Leg extensor power (Watt)	Data source	Note
Calibration	Average	72.2	238.0	ADNFS and NHANES I	
Validation	Average	76.5	238.0	ADNFS and NHANES III	*1
	Elderly-male	79.5	152.4	SK and HS	
	Eldelry-female	67.9	87.2	SK and HS	
	Young-male	79.2	353.0	AD and HS	
	Young-female	66.9	202.3	AD and HS	
	Average	76.6	238.0	AD and HS	

*1: Used in comparison with Templer's model.

ADNFS: Allied Dunbar National Fitness Survey (Sports Council et al, 1992)

NHAMES I: National Health and Nutrition Examination Survey from 1971to 74

NHAMES III: National Health and Nutrition Examination Survey from 1988 to 94

NHAMES data are from Ogden et al (2004)

SK: Skelton et al (1994)

HS: Health Survey for England 2004 (Health and Social Care Information Centre, 2005)

The used values are from unweighted values in the report

Table X. Input characteristics of stairs

		Stair type	Number of steps	Riser height (mm)	Tread depth (mm)	Gradient (deg)
Stairs used in the experiment	Stair 1	dexitral dog-leg	12	185	230	38.8
	Stair 2	dexitral dog-leg	12	175	250	35.0
	Stair 3	dexitral dog-leg	15	157	267	30.5
	Stair 4	dexitral dog-leg	9	152	332	24.6
Stairs used in validation	Underground station	dexitral dog-leg	15	150	290	27.3
	University	dexitral dog-leg	15	157	267	30.5

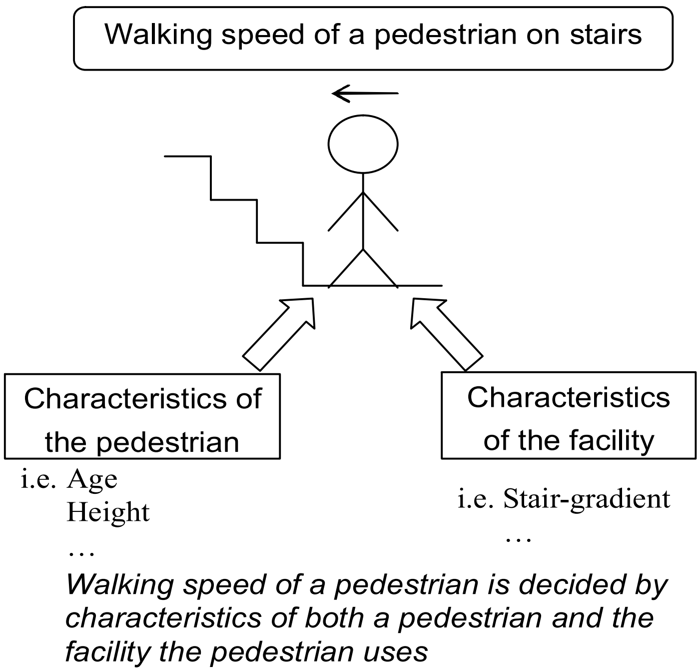

Figure 1. Schematic representation of the model that takes account of characteristics of a pedestrian and of the facility the pedestrian uses

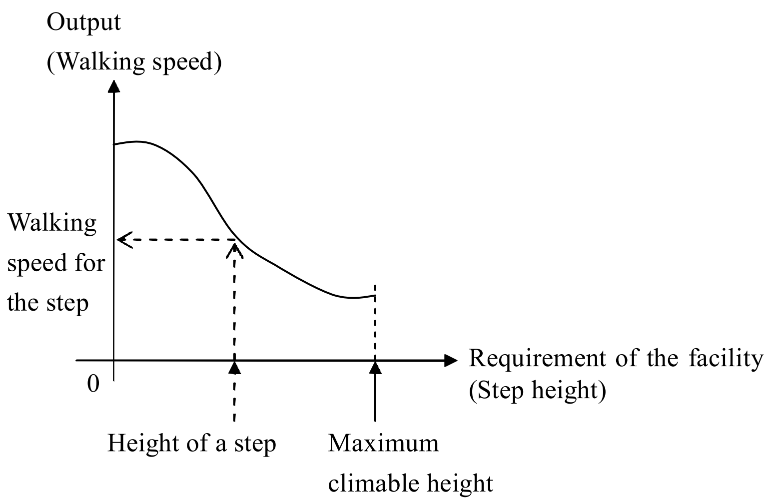

Figure 2. A schematic representation of how the proposed framework works. According to his physical capability, each pedestrian has a unique curve for the requirement of the facility and the output for each action.

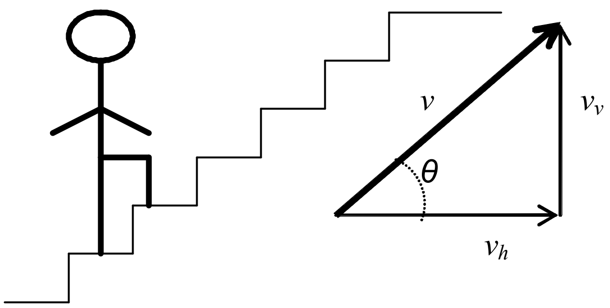

Figure 3. Stair-gradient and components of the walking speed

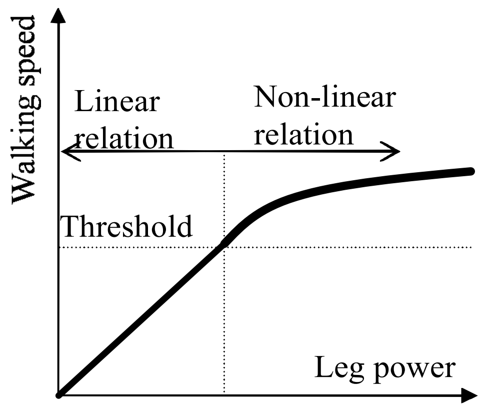

Figure 4. Threshold model

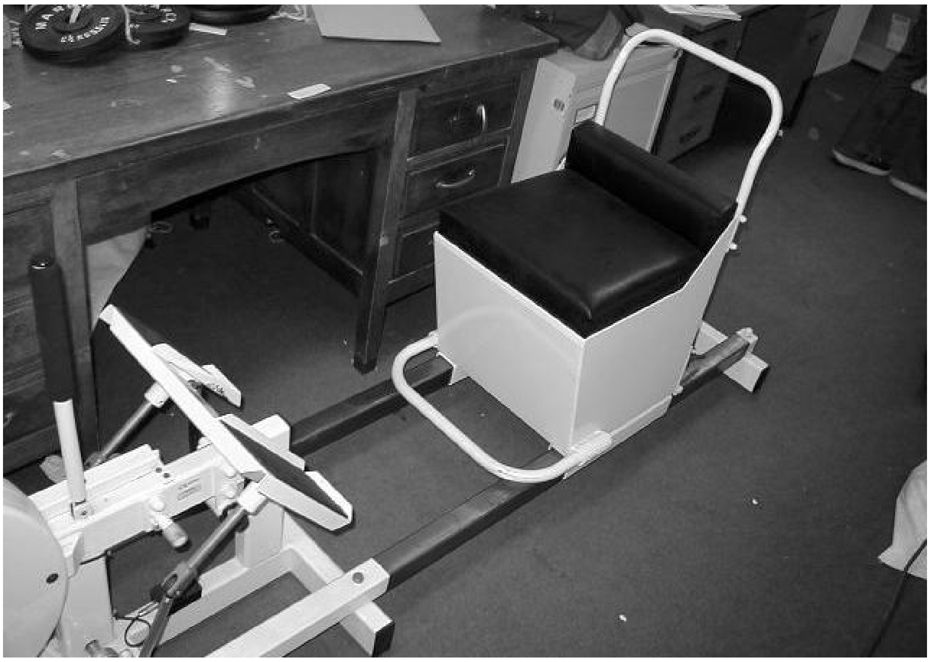

Figure 5. Leg power rig

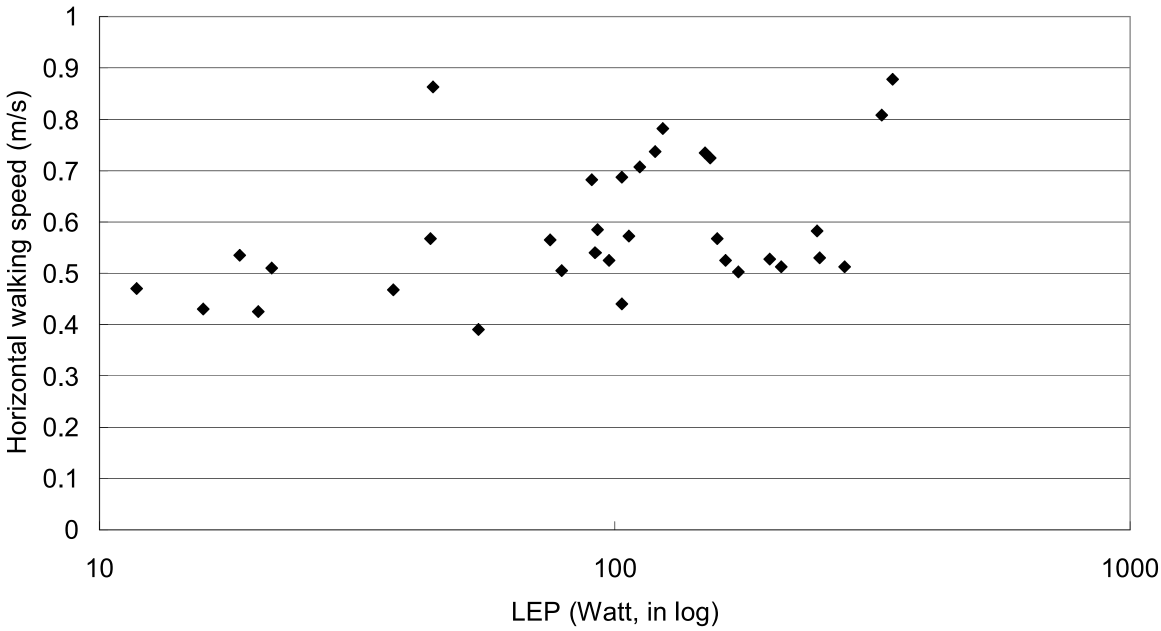

Figure 6. Relationship between leg extensor power and normal ascending speeds.

Speeds are in the horizontal.

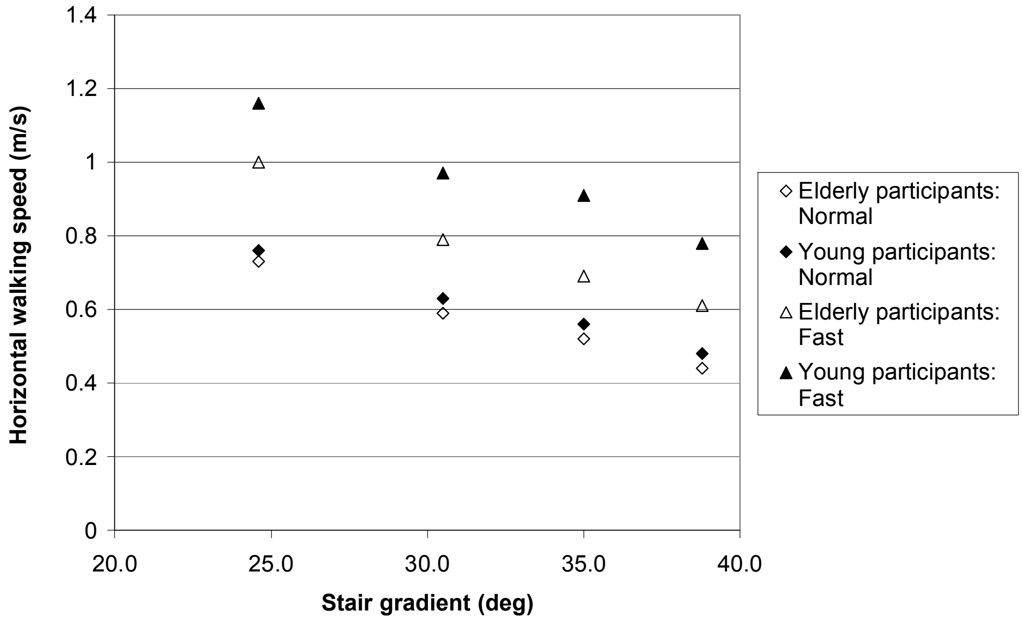

Figure 7. Relationship between stair-gradients and ascending speeds. Speeds are in the horizontal direction and averaged values of participants of each group.

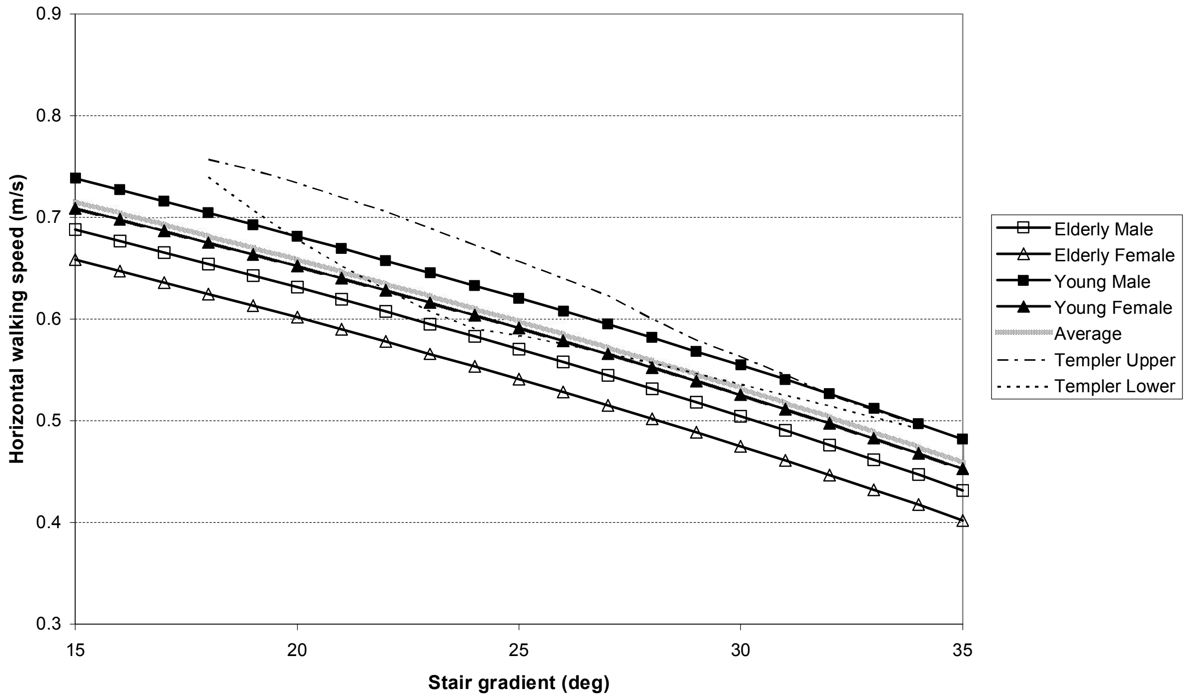

Figure 8. Predicted ascending walking speeds

(speeds are in the horizontal direction)

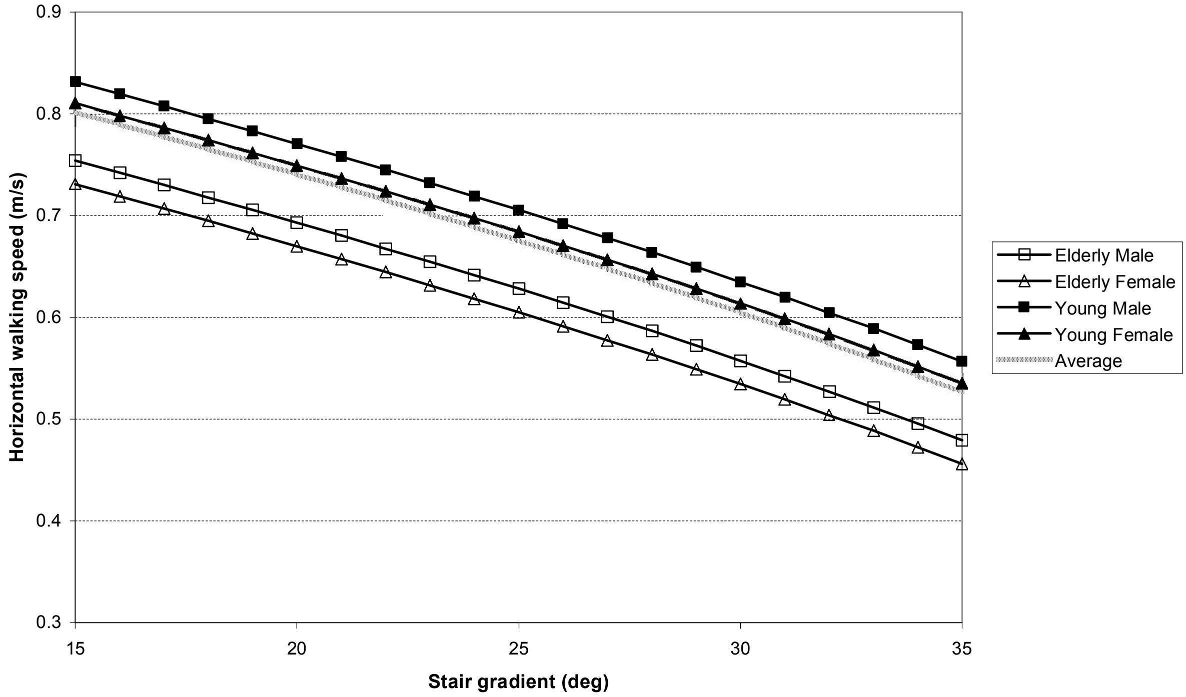

Figure 9. Predicted descending walking speeds

(speeds are in the horizontal direction)