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# The effect of an ageing and less fit population on the ability of people to egress buildings

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ABSTRACT

The functional capability of building occupants to egress from buildings is likely to change as populations age and become less fit. A review of the current health literature suggests obesity can be used to determine the likely reduction in walking speed and also as a marker for other egress related factors such as the risk of falls. This paper examines the possible effects of gender, age and obesity and uses a Monte Carlo network evacuation model to examine whether these changes will significantly increase the total evacuation time from an exemplar high-rise building. Modelling results suggest that total evacuation times may increase by up to 20% when comparing historical data from Canada in 1971 with a future New Zealand scenario for 2031.



## 1. Introduction

Much of the original work on people movement, for example by Fruin (1987) and Pauls (1987), was conducted several decades ago and there is concern from researchers that the data may not be relevant to today and the future (Pauls, 2007). The population profile will change over the next few decades due to ageing and a reduction in the level of fitness due an ever increasing sedentary lifestyle (Booth et al., 2002). This poses the question as to whether the functional ability of a significant percentage of the population of any of Western Society, and Asia for that matter, will be sufficient to survive the physical challenge of evacuation in many of the emergencies that may beset the buildings that are being designed at this moment in time.

This paper addresses aspects of future population profiles that may affect evacuation and in particular in a New Zealand context by considering changes in age and gender profiles; how age and gender affect walking speed and walking capacity; changes in the 'fitness' profile of the population; how body mass index (BMI) affects walking speed and walking capacity; what other factors that will impact on occupant functional ability due to physical inactivity and how might these trends affect building evacuation.

This paper firstly discusses the potential effects of functional capacity on evacuation by examining recent health literature. Since walking speed is normally used in evacuation models, the paper then provides a comparative analyses of evacuation times using a Monte Carlo network evacuation model that accounts for certain functional capacity measures. The analyses consider the previous work published by Pauls (1987), population data from Canada ca. the time of Pauls' work, data for recent New Zealand population characteristics and projected New Zealand data for 2030/31.

## 2. Functional ability

For many people the task of walking down multiple flights of stairs, over irregular surfaces, or in fact in any environment for that matter will depend on whether the person has the capacity and therefore the ability to undertake and complete such a challenge. Functional capacity refers to the capability of performing tasks and activities that people find necessary in their lives. It should be possible to evaluate whether or not a person has the functional capacity to undertake an evacuation of a facility successfully if this task and activity is viewed as part of a person's job or a necessary activity of daily living (ADL) (APTA, 2009). This would be possible when viewing various walking test regimes (Hulens et al., 2003; Fritz and Lusardi, 2009; Al-Abdulwahab, 1999; Kang and Dingwell, 2008), but unfortunately the activity of evacuation is not classified as an ADL although some attempts have been made using similar tests in assessing occupant characteristics for evacuation models (Kady and Davis, 2008).

People may be able walk at a certain speed such as demonstrated in standard 6 or 10 min walking tests (Fritz and Lusardi, 2009) but these tests on their own do not necessarily reflect the person's walking capacity which also relies on strength, endurance, and stability as well as many other factors (Al-Abdulwahab, 1999). Walking capacity is synonymous with functional capacity and therefore the question is not just one of fitness but also the degree

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to which other conditions such as age and obesity together with their other morbidities will limit this capacity (Kang and Dingwell, 2008; Ayis et al., 2007; Al-Abdulwahab, 1999; Hulens et al., 2003). Defining the environment over and through which the people will have to travel is therefore an essential part of the assessment of the capacity (Reeves et al., 2008; Hamel and Kavanagh, 2004; Haslam et al., 2006 and Ozanne-Smith et al., 2008) as some environments (e.g. stairs) will be much more demanding. Part of the evacuation journey may involve people taking a rest because of fatigue (Averill et al., 2007; Galea et al., 2008) or dizziness or merely to rebuild their confidence should they have a fear of falling (MacLennan, 2010).

Obesity is a metabolic disease (Booth et al., 2002) and can be linked directly to physical inactivity. Age relates directly to a deterioration of physical, mental, neurological and other functions (Kang and Dingwell, 2008; Lord et al., 2006; Ozanne-Smith et al., 2008; Stel et al., 2003; Reeves et al., 2008). The prevalence of obesity in old age will increase as indicated by the trends in obesity by simply extrapolating from such studies as the NHANES studies between 1976 and 1992 (Kady and Davis, 2008) so that these two categories are appropriate for the assessment of walking capacity in egress calculations. The multiple functional limitations associated with ageing (including the preponderance of musculoskeletal pain) can be summarised by Ayis et al. (2007) when they show the relationship between ageing, health conditions and walking capacity in Fig. 1. In Fig. 1c the maximum walking time represents the maximum walking time before stopping. A reduction in walking ability results in a shorter walking time due to increased pain or fear that they will fall and a reduced mean walking speed.

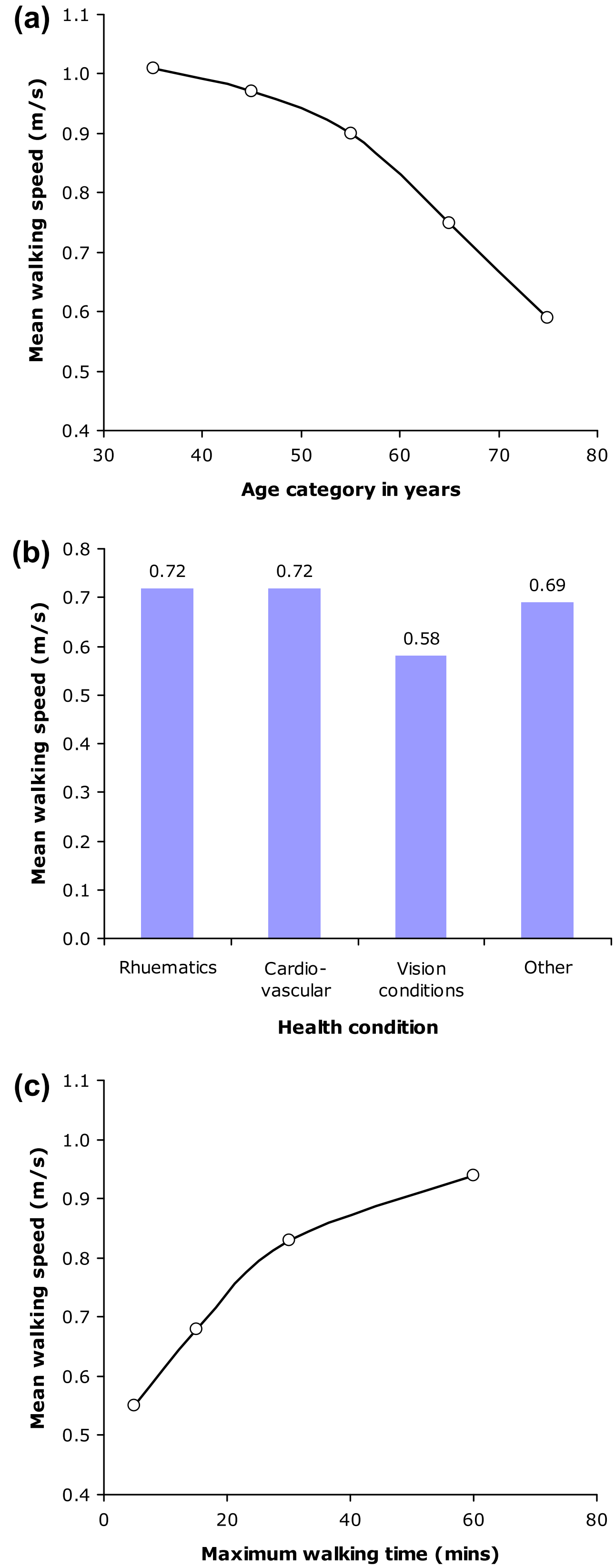


**Fig. 1.** Walking speeds, health condition and walking ability/capacity (adapted from Aysi et al., 2007); (a) mean walking speed versus age; (b) mean walking speed versus health condition; (c) mean walking speed versus walking ability.

*2.1. Obesity, walking speed and walking capacity*

Human beings are wired to be active and a sedentary lifestyle can be directly connected to numerous chronic health conditions such as cancer, coronary heart disease, hypertension, other respiratory conditions, Type 2 diabetes, neurological disorders and obesity (Booth et al., 2002). Type 2 diabetes and obesity virtually go hand in hand (Booth et al., 2002) and are associated with a decline in overall health and physical functioning.

He and Baker (2004) showed in their longitudinal study that those participants who reported that they were obese at a baseline gained weight over the span of the study and were more likely to develop functional limitations that included mobility. The questions that the respondents were asked by He and Baker (2004) included extensive questions on the type of movement and degree of fitness that would be required for an evacuation. Obesity and indeed the degree of fat mass can also be directly linked with increases in musuloskeletal pain and various arthritic conditions (Ayis et al., 2007; Hulens et al., 2003; Booth et al., 2002) which impacts directly on walking speed and capacity. Thus the health science literature appears to establish that there are direct links between morbid obesity and various functional abilities such as stability, mobility and those other normal ADL's (Mhurchu et al., 2004; He and Baker, 2004; Hue et al., 2007) although results from Peacock et al. (2009) do not support slowing of evacuation speeds due to obesity or fitness however the authors note that additional study is needed.

Body mass index is used as a classification tool to establish a person's level of fitness. It is defined as a person's mass divided by the square of their height measured in kilogrammes and metres respectively. The World Health Organisation BMI classification scale (2009) is:

- <17.5 kg/m$^2$ Anorexia
- 17.5–18.5 kg/m$^2$ Underweight
- 18.5–25 kg/m$^2$ Optimal
- 25–30 kg/m$^2$ Overweight
- 30–40 kg/m$^2$ Obese
- >40 kg/m$^2$ Morbidly obese

Mhurchu et al. (2004) in their study on obesity and the associated health-related quality of life found that obesity is associated with lower scores in the physical and psychological domains. More than 38% of their sample had two or more co-morbidities where Type 2 Diabetes is the most common and could over time lead to other conditions affecting mobility such as neuropathy and cognitive dysfunction (neurological condition) which further affects mobility and spatial perception.

Studies show that the groups that are directly associated with functional limitations in their walking and stair climbing ability are those who are obese and morbidly obese. For example, walking ability in the group of women studied by Hue et al. (2007) was restricted in the morbidly obese and was directly attributed to anthropometric, physical fitness and physical activity parameters. The distances covered by the various participants over the 6 min of the walking test varied directly according to their fat mass distribution as well as their BMI classification. Similarly Hulens et al. (2003) show how conditions that interfere with walking capacity become more prevalent in the obese and morbidly obese compared to lean body sizes (Fig. 2).

Sarcopenia or the loss of muscle mass is also directly associated with obesity and strength is associated with walking capacity and endurance (Booth et al., 2002). Breathlessness or Dysponea is often associated with obesity in terms of the functioning of the respiratory system (Booth et al., 2002). This has a direct affect on evacuation in terms of the 'work' required to complete the physical challenge. MacLennan (2011) through the dissemination of data from a 'larger persons' (i.e. people with a BMI of 30 and above) focus group and its triangulation with video images of people resting during stair descent in some of the trial evacuation case studies demonstrates that walking ability should be factored in. Resting is part of the journey and therefore needs either to be factored into the walking speed or into the simulation as an independent variable.

If the projections made in the next section persist then the challenge for evacuation design and management will need to be met. The current level of building populations that will need either special assistance or other alternative strategies will increase from that found by current researchers (Averill et al., 2007) of some 6%. One of the critical data (MacLennan et al., 2008) is that the percentage of population profiles in some western countries have the morbidly obese running at 5% and this could easily grow to 10% or more by the year 2031.

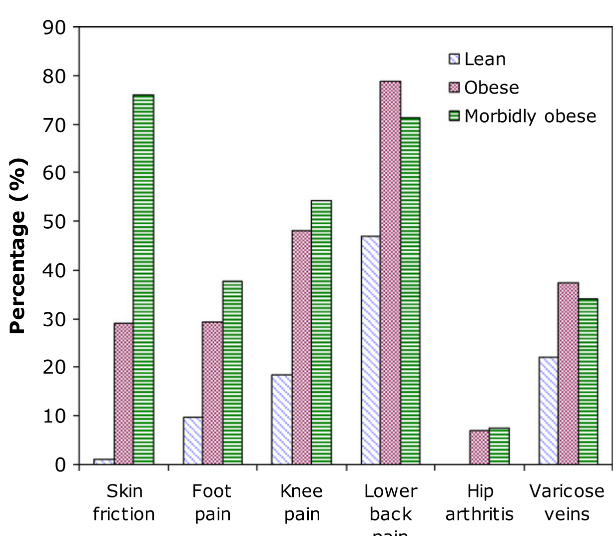


**Fig. 2.** Conditions interfering with walking capacity (adapted from Hulens et al., 2003).

## 2.2. Spatial considerations

MacLennan has demonstrated in a subsidiary study (2008) to that mentioned earlier (MacLennan, 2010) that body space has increased along with obesity. Body fat is usually located around the mid-region of the body as clearly indicated in the CT Scan data (Geraghty and Boone, 2003) used by MacLennan to derive a range of body ellipses directly related to waist circumference and BMI. MacLennan showed an increase from the maximum ellipse put forward by Crowd Dynamics (2007) of 0.28 $m^2$ to 0.44 $m^2$ which is an increase of some 58%. This can be shown dimensionally to create a blockage in fire stairs in Australasia which are usually in the order of 1000 mm between handrails. The obese and morbidly obese person will most likely be slow movers (Hulens et al., 2003; Ayis et al., 2007) due to their own capacity or environmental constraints (MacLennan et al., 2008). They are most likely to be evacuating as part of a group (Galea et al., 2008; MacLennan et al., 2008) that exhibits altruistic behaviour. People behind may wish but be loathe to overtake and hence some tension may be created. The net result may be a blockage of some sort which has been evident, although not extensively reported in the literature (Proulx et al., 2007). The spatial considerations therefore relate to the question of the provision of space in corridors and stairs and other escape routes or providing a potential solution via some other form of evacuation method.

## 2.3. Falls

Functional ability is measured with tests that deal with balance, strength and mobility with the most marked measure being a decrease in stability. Naturally then ageing is associated with an increase in the risk of falling as well as the development of the fear of falling (Stel et al., 2003). Stel et al. show that fallers had features that characterised them as being high risk when engaged in walking or stair climbing (e.g. age, osteoarthritis, hypertension, reduced vision, low strength, cognitive impairments, fear of falling, depression, musuloskeletal pain, other mobility limitations, and weight). Many of the chronic conditions brought by ageing serve as functional limitations to moving around the built environment. Stel et al. show that functional limitations can directly predict the risk of falling and hence the lack of confidence that would be associated with reaching safety in an evacuation. The most important aspect here is that the fear of falling is synonymous with the degree of confidence that the elderly have with walking and stair climbing (Lopes et al., 2009; Lord et al., 2006). Lord et al. (2006) show a direct correlation between the deterioration of sensori-motor senses (vision, hearing, peripheral sensation due to such things as neuropathy, vestibular sense, strength and an increase in reaction time) and falls. Other chronic conditions brought on not only by ageing but by physical inactivity also play a part. Hue et al. (2007) tested for balance and showed that stability was directly related to body weight as well as age. Vision impairment was also included in the test and shows that as vision reduces, stability is also affected. All of the above result in a reduction of functional ability and confirm that falling is due to a multitude of factors. Walking speed tests have also similarly been shown to be a strong predictor of falling and can be linked to the prediction of other functional limitations (Fritz and Lusardi, 2009).

The risk of falling and the ensuing blockage therefore needs to be factored into an evacuation calculation. Similar to Bruce et al. (2002), participants in focus groups of 'larger persons' in a current study being undertaken by MacLennan (2011) have confirmed this and have further stated their fear of going down multiple flights of stairs. Trial evacuations undertaken during the 1980s and as part of MacLennan (2011) current studies also confirm these findings in the reduction in stair descent speed over this period.

## 3. Modelling inputs

A range of modelling inputs was required to enable an assessment of the effect of gender, age and obesity on evacuation. Since the original work presented by Pauls (1987) was as the result of studies conducted in Canada in the 1970s it was useful to obtain relevant data from that era. Recent population data from New Zealand and predictions for the future up to 2031 (to correspond with MacLennan et al., 2008) were sourced.

### *3.1. Age and gender profiles*

To examine the changing age and gender profile of the New Zealand population, data for 1996 and 2006 was obtained from Statistics New Zealand (2009a). Predictions for the future age and gender profile for 2011 and 2031 were also sourced from Statistics New Zealand (2009b). Age and gender profiles were obtained for Canada for 1971 and 1976 (Basavarajappa and Ram, 2008). Fig. 3 shows the profiles obtained for this research. The New Zealand data shows the effect of the ageing population between 1996 and 2006 with trends continuing for the 2011 and 2031 projections.

### *3.2. Obesity*

Data for New Zealand population BMI values is available from Ministry of Health (2004) for 2002/03 and other data from World Health Organisation (2009) covering 1997, 2002/04 and 2006/07. Some data accounts for specific ethnic groups such as Maori and Pacific Islanders which show a greater percentage of people with larger body sizes compared to European and Asian groups. However it was found that the data sets are not complete for the full range of BMI categories and so an element of interpretation was necessary for this study in order to assess overall trends for the decade (Fig. 4). Similarly BMI data for the 1970–1972 Canadian population is available from the World Health Organisation (2009). It was noted that none of the data includes BMI values greater than 40 kg/m$^2$ and although this is not unexpected for data that goes back to the 1970s where people had on average smaller body proportions it did restrict the ability to get corresponding predictions for this larger body size when compared to the 5–10% suggested by MacLennan et al. (2008).

Using the data given in Fig. 4, exponential or logarithmic best-fit functions were applied as appropriate to each dataset. From these functions the trend in BMI into the future was assessed and hence the increase in average BMI in New Zealand as a function of time was determined. Mhurchu et al. (2004) gave predictions for increase in BMI in 2011 with 'business as usual' such that the change in average BMI is around 105% for both male and female from 1997 to 2011. By using the best-fit functions, determining the proportion of the future population within each BMI category (Fig. 5) and calculating weighed average BMI values this research predicts a 108% increase in average BMI for males and a 104% increase in average BMI for females by 2011. The reasonable match between the two predictions allowed for the change in BMI between 2006 and 2031 (Fig. 5) to be made using the same approach as that used to compare with Mhurchu et al. (2004). Clearly the assumption made in this analysis that BMI values will continue to increase may not be found to be correct if the 'business as usual' model is not borne out in the future.

### *3.3. Walking speed*

To create a functional relationship between gender, age and walking speed this work used Ando et al.'s data (as cited by Smith, 1995) as its starting point. Alternative data for walking speed from Fritz and Lusardi (2009) could have been selected and it was noted that their data show slightly lower maximum speeds. Unfortunately Ando et al.'s data only extends to an age of 70 years so the

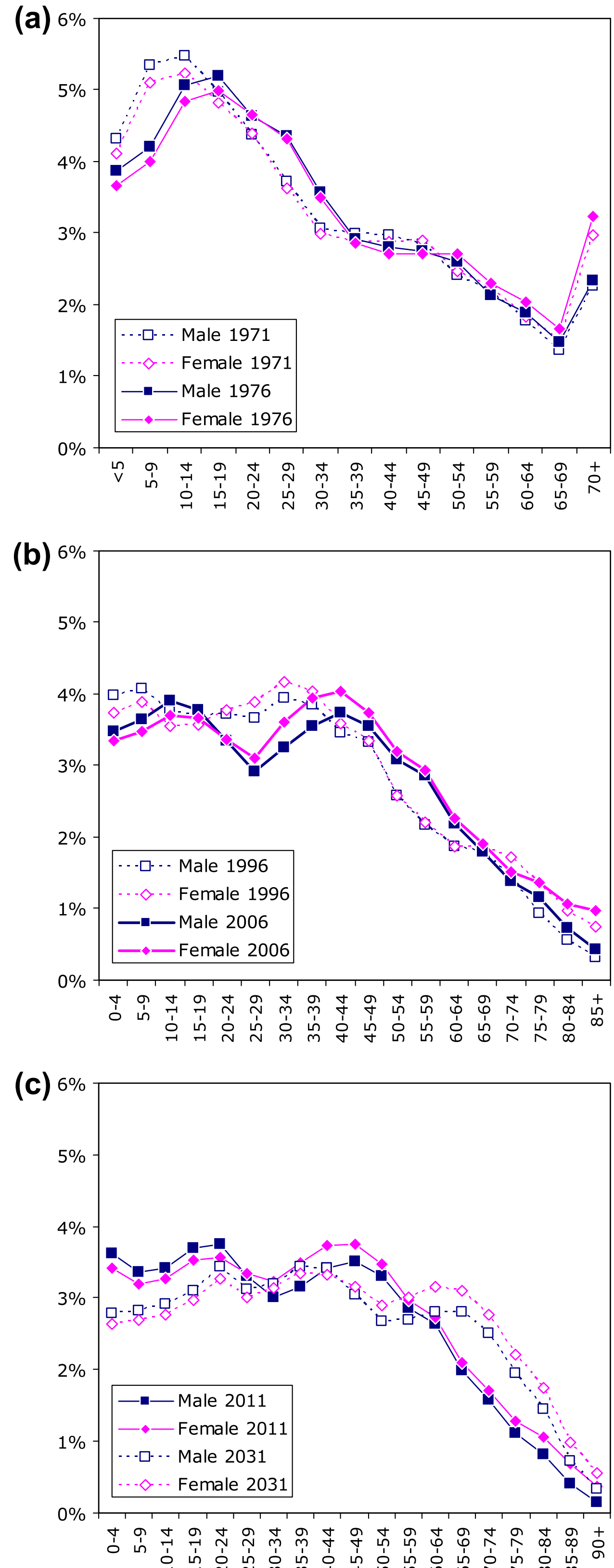


**Fig. 3.** Age and gender profiles (a) Canada 1971 and 1976; (b) New Zealand 1996 and 2006; (c) projections for New Zealand 2011 and 2031.

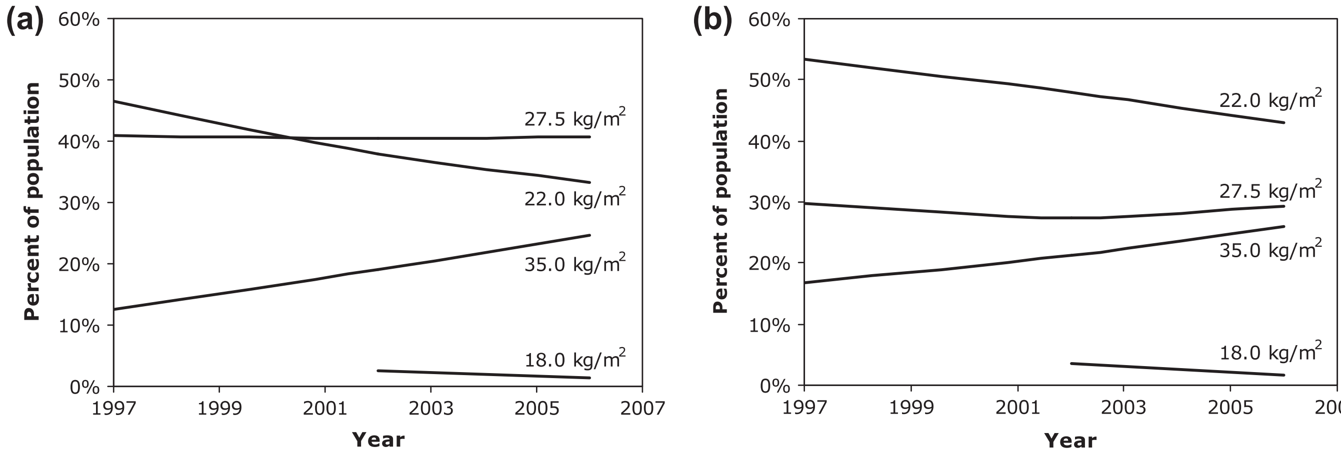


**Fig. 4.** Trends in BMI categories for New Zealand between 1997 and 2006; (a) males (b) females.

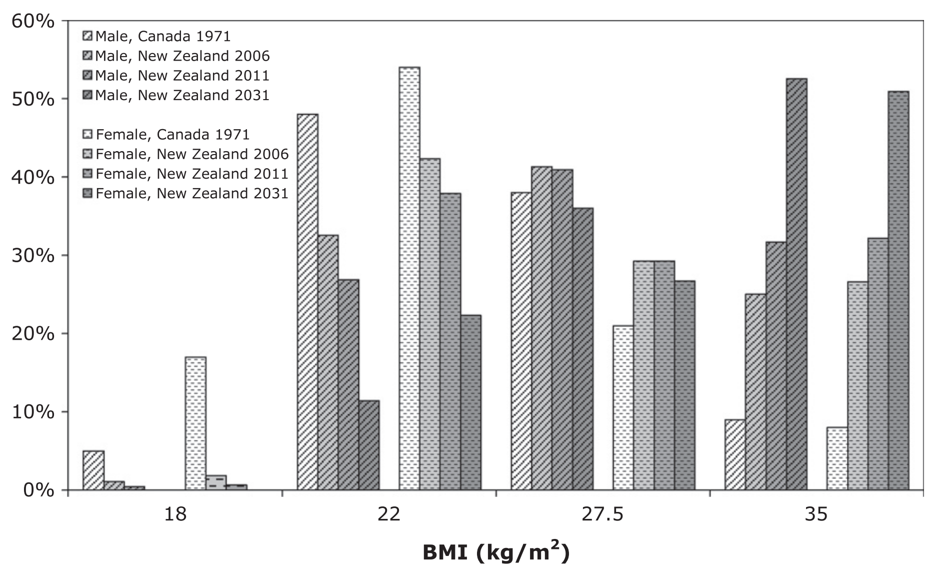


**Fig. 5.** The 1971 distribution of BMI for the Canadian population, 2006 distribution of BMI for the New Zealand population and predictions for New Zealand in 2011 and 2031 assuming a 'business as usual' model.

lines were extrapolated to 100 to allow for the ageing population profiles. The extrapolations were determined using best fit polynomial functions to Ando's original data. The polynomials are fifth and sixth order for female and male respectively and although these might be considered excessively complex they yielded useable values that are considered here as reasonable. Ando et al.'s data also does not include any variability in the walking speed so the distributions for speed at a given by Lord et al. (2005) were applied to the Ando et al. data (Fig. 6). It was recognised that the Lord et al. (2005) data is only specified for three broad age bands and mean values somewhat differ from Ando et al. but was sufficient for this research. When compared with Ayis et al.'s (2007) data it was observed that the inclusion of musculoskeletal effects reduce mean walking speeds as might be expected.

When the effect of BMI is factored into movement the data suggests that the walking speed of obese people is approximately 90% of non-obese (Hills et al., 2006; Hulens et al., 2003). Similar results are obtained for elderly females (average age 76) walking at their definition of a 'fast' pace from Leiper and Cralk (1991). Additional information from Pires et al. (2007) and Enright and Sherrill (1998) was obtained and plotted in Fig. 7 however the exact age ranges and BMI values were not always clear in the literature so

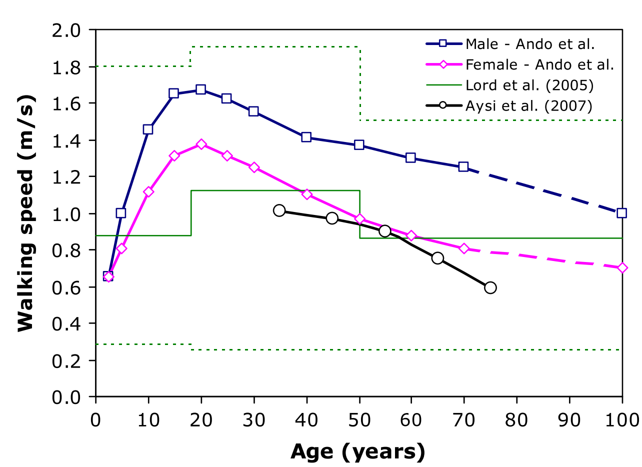


**Fig. 6.** Comparison of walking speed as a function of gender and age from an adaptation of Ando et al. (dashed lines show extrapolation to 100 years) with mean, maximum and minimum range values (dashed lines) from Lord et al. (2005) and data from Aysi et al. (2007).

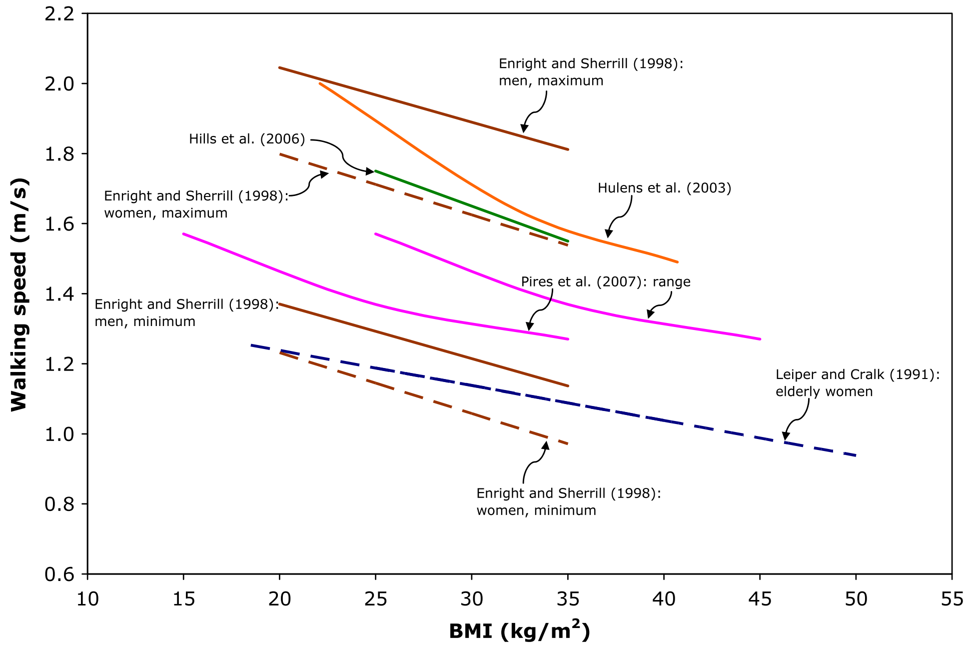


**Fig. 7.** Walking speed as a function of BMI values given by various researchers.

some interpretation was required. For example, Leiper and Cralk (1991) provide a best-fit equation to their data as a function of age and BMI but do not specify any limits. Here BMI values corresponding to the range between optimal and an arbitrary maximum of 50 kg/m$^2$ to account for morbidly obese have been illustrated. Pires et al. (2007) only give their BMI values in terms of broad ranges of <25 kg/m$^2$, 25–35 kg/m$^2$ and >35 kg/m$^2$ so selected BMI values in the ranges of 15–25 kg/m$^2$, 25–35 kg/m$^2$ and 35–45 kg/m$^2$ have been used to generate the curves shown in Fig. 7.

It was noted that there was a wide range of absolute walking speeds quoted in the literature and this data was often higher than Ando et al.'s data and the 'typical' 1.20 m/s that might be assumed for egress modelling. Regardless of the absolute values, it was clear that the rate of reduction in walking speed as a function of BMI quoted in the literature is very similar. To overcome the wide variation, all of the walking speed data was normalised and an appropriate 'reduction factor' equation was determined (Fig. 8). The reduction factor assumed no reduction at BMI values less than or equal to 23 kg/m$^2$ (i.e. mid-way of the optimal range) and there were no gender or age effects on top of already determined factors. This reduction factor was then applied to account for the individual's BMI to the age and gender related walking speed that was obtained from the combination of Ando et al. and Lord et al. shown in Fig. 6. Although it is noted that obesity increases with age, in the context of the modelling these have been taken to be independent factors since much of the data and models that were available in the literature did not clearly include such dependency. The work by Enright and Sherrill (1998) did examine walking speed as a function of BMI, age and gender but was limited to BMI values of the order of 20–35 kg/m$^3$ and ages around 40–80 whereas it was desirable to have younger people as well as larger BMI values for the modelling study.

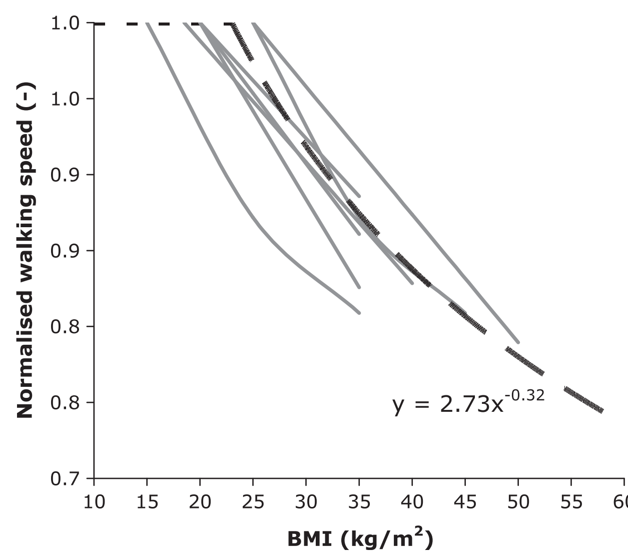


**Fig. 8.** Normalised walking speed data and the 'reduction factor' equation (shown as the dashed line) used to relate change in walking speed with BMI.

## 4. EvacuatioNZ network modelling

The research used a Monte Carlo-based network evacuation model referred to as EvacuatioNZ (Spearpoint, 2009). This model uses a coarse network approach to represent a building to reduce computational times allowing for many repeat runs to be completed. People are represented as individuals with their own behavioural and personal attributes. Movement speeds are based on the equations provided by Gwynne and Rosenbaum (2008) and the model also accounts for the effect of door constrictions and stair configurations on the people flow using the effective width concept (Proulx, 2008). The model has the ability to employ the normal, log-normal, uniform, triangular or Weibull distributions shapes whenever a statistical distribution can be specified for an input parameter and these distributions can be truncated at a specified upper and/or lower limit.

Previous work has examined the performance of the model components (Spearpoint, 2009) as well as applying the model to a case study building (Ko et al., 2007). Access to the source code allowed this research to develop new input data structures and

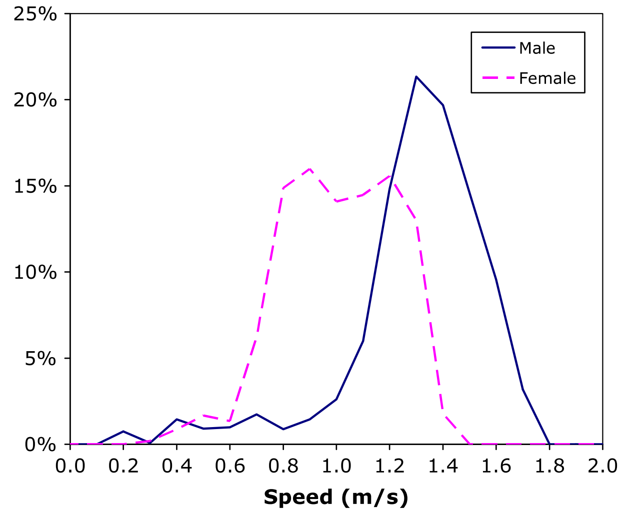


**Fig. 9.** Distribution of walking speeds generated by EvacuatioNZ for 5000 random people using 2006 New Zealand age and BMI data.

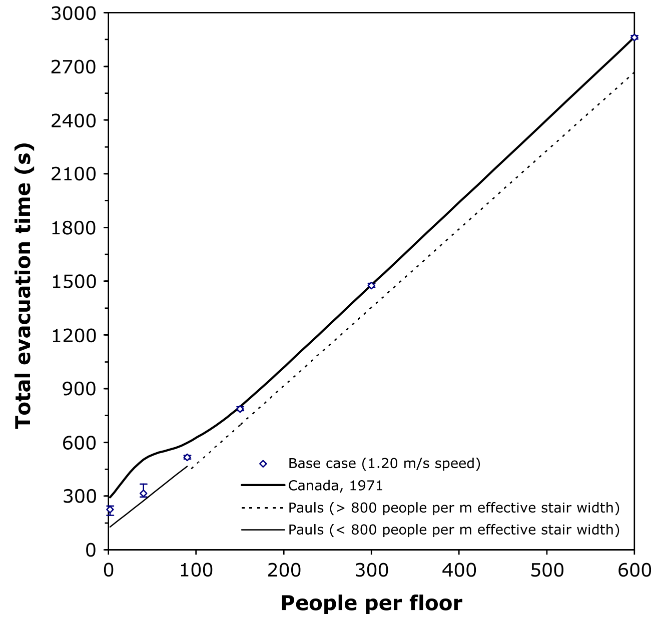


**Fig. 10.** Comparison of calculated total evacuation time from EvacuatioNZ for the base case, 1971 Canadian population data and Pauls (1987).

algorithms using the current statistical and health literature discussed previously. In particular EvacuatioNZ was structured to accommodate walking capacity for a whole range of building population profiles focusing mainly on the limitations imposed by age and obesity.

The previous work by Spearpoint (2009) included using the EvacuatioNZ model for an exemplar high-rise building evacuation analysis. A scenario was created in the previous work where all occupants were assigned a fixed maximum walking speed of 1.20 m/s to correspond with the example given by Gwynne and Rosenbaum (2008) and comparison was made to the work by Pauls (1987). This paper uses the earlier fixed walking speed scenario as a base case for further comparison to examine how much the total egress time might change by 2030/31. The same geometrical input was used in this work for the exemplar high-rise building as that reported by Spearpoint (2009). The occupant age distributions were proportioned to statistical or predicted gender, age and BMI data depending on the scenario but no account was made for ethnic groups within the population.

The capability of the EvacuatioNZ model to create appropriate population groups was successfully validated against the 2006 New Zealand statistics. Age and gender profiles from the previously described Statistics New Zealand data and BMI data from the World Health Organisation were used as the input distributions. EvacuatioNZ was used to randomly generate 5000 people and the distribution of walking speeds for males and females are shown in Fig. 9.

For the following scenarios occupant numbers were fixed on each floor (2, 40, 90, 150, 300 and 600 people per floor) and there was no pre-evacuation delay applied. Occupants were assumed to start at uniformally distributed random distances from their first exit where the maximum distance was the sum of the length and breadth dimensions of the space. The simulations were run to 0.0005% convergence in the predicted total evacuation time which required on the order of 50–500 simulations per scenario.

### 4.1. Historical Canadian case

Evacuations were simulated using the 1971 Canadian data for gender, age profiles and BMI values using a typical office age range (17–65 for men, 17–60 for women) since Pauls' original work was taken from office evacuation studies. Total evacuation time results (Fig. 10) from EvacuatioNZ generally show a reasonable match between the base case scenario, the 1971 Canadian population data and the equation published by Pauls (1987). Similar results were obtained using the 1976 Canadian gender and age profiles. These results gave confidence in the general capability of the EvacuatioNZ model and provided a case for comparison with further scenarios.

### 4.2. Recent and future New Zealand cases

The modelling and analysis considered a comparison of three cases: the original base case scenario (Spearpoint, 2009); age, gender and BMI profiles for New Zealand in 2006 and age, gender and BMI profile predictions for New Zealand in 2031. An age range from 17 to 72 regardless of gender was applied in the New Zealand scenarios so as to avoid the age extremes and to allow for a comparison with the previous Canadian scenario. An upper age limit of 72 was used here since Pitt-Catsouphes and Smyer (2006), for example, note that many adults in the US are working later into their 60s and 70s and may make a gradual transition from full-time employment into retirement. It is assumed that a similar trend is occurring in New Zealand.

The analyses show a marked difference between the base case and the two New Zealand population profile cases for 2006 and 2031 (Fig. 11). Mean values for the total evacuation time for the base case are noticeably smaller when the number of people per floor are less than 150 whereas values are similar at higher numbers. The ranges of maximum and minimum total evacuation times are considerably wider for the population profile cases and those ranges typically reduce with an increase in people per floor. Results tend to match at these higher population numbers because it was the queuing that drove the total evacuation time rather that individual walking speeds. Fig. 12 shows a more detailed investigation of the spread of calculated total evacuation times from the EvacuatioNZ model where long tails in the distributions can be seen. Total evacuation time results for the base case do not vary significantly as would be expected as the walking speed is fixed at 1.20 m/s. Results for the New Zealand cases show a skew to the higher total evacuation times at the lower occupant loads.

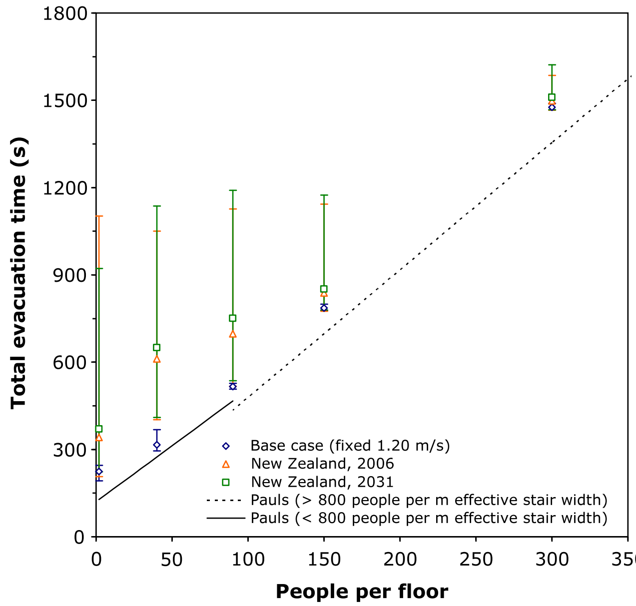


**Fig. 11.** Total evacuation times obtained from EvacuatioNZ for the base case, 2006 and 2031 New Zealand population scenarios. Symbols show the mean total evacuation times and bars indicate the range.

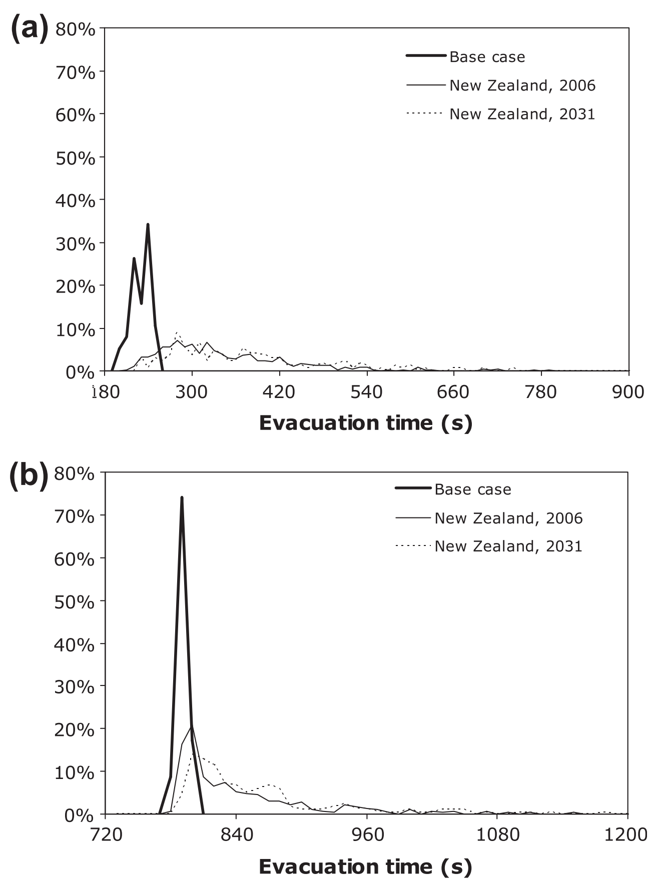


**Fig. 12.** Distributions of calculated total evacuation times from EvacuatioNZ for the base case, 2006 New Zealand population scenario and 2031 New Zealand population scenario; (a) 2 people per floor (b) 150 people per floor.

Modelling occupants with a typical maximum walking speed of 1.20 m/s as suggested by Gwynne and Rosenbaum (2008) results in similar evacuation times for the Canadian 1971 population profiles and so could be considered an appropriate methodology. However larger total evacuation times for the 2006 and 2031 New Zealand cases when the effects of age, gender and BMI are considered and would therefore suggest a typical maximum walking speed of 1.20 m/s may not be sufficiently conservative for a design approach. In general the comparison of the results show that at 'low' occupant numbers the total evacuation time increased by 5–8% between 2006 and 2031 New Zealand cases however there was little change at 'high' occupant numbers because of queues. If the Canadian analysis is considered to be representative of population profiles in New Zealand for 1971 then the evacuation time increase is up to around 20% for New Zealand 2031 using the equivalent walking speed reduction algorithm. Clearly the extreme total evacuation times are as a result of a small number of older, larger occupants who are consequently slower than the bulk of the population.

## 5. Discussion

The health literature for New Zealand shows that obesity has increased over the years and if a business-as-usual scenario is considered then obesity is likely to continue to increase. The literature also shows that obesity impacts on many impairments such as a reduction in balance, an increase in osteoarthritis etc. which will not only reduce occupant speed but the distance that evacuees are capable of covering. Similar to Ayis et al. (2007), Peacock et al. (2009) have found that distance travelled is one of the major predictors of descent speed.

The potential for plug flows exists when people slow down due to exhaustion, injury (Peacock et al., 2009) or a fear of falling. Exhaustion relates to the distance travelled and the level of impairment i.e. how long is before the person stops or the degree to which they hold onto a handrail or both handrails. MacLennan (2010) has shown that even with a stair width of 1200 mm between handrails that some people will hold onto both for support. The increase in obesity and thus body size also relates to a marked increase in the potential for plug flow where there is no room on the landings for people to rest. Group altruism can be a further cause of plug flow where an obese person may need help (Dwyer and Flynn, 2006). Adams and Galea (2010) measured the performance of numerous devices for the evacuation of people needing assistance where sometimes four helpers were necessary. This would create a plug and run the risk of further hold ups due to falling. A falling person and the addition of one or more helpers could block the flow for a period of time. A fall in one evacuation study on a 36 storey building observed by MacLennan (2011) altered the pattern of evacuation.

Clearly the modelling that has been conducted in this research has only considered the effect on evacuation speed as it relates to age, gender and BMI. These factors have been treated in a fairly simplistic manner yet only considering these factors results in total evacuation times that are likely to be longer than when a fixed maximum walking speed is considered.

The problem with much of the research to date is the failure to address the differences between buildings. Peacock et al. (2009) show that there are many factors that affect travel speed and evacuation time other than occupant density. A 'case study research method', such as that undertaken by MacLennan (2011), allows comparisons to be made between the buildings and trends to be established. Generalisation is dangerous unless trends are established between different buildings and evacuations. This research suggests that the design of high-rise buildings for evacuation needs to consider the ability of vulnerable people to successfully use stairs and also the potential impact of those vulnerable people on the other building users. An evacuation scenario approach to design is needed so that more factors can be taken into account and management in use recommendations can be made for each building.

Finally, this research highlights the need for ongoing consideration for the use of lifts as part of an evacuation strategy whether the strategy is targeted towards vulnerable occupants or available to all building occupants. Different lift utilisation strategies can be examined in order to provide more effective evacuation outcomes.

## 6. Conclusions

This paper shows how the functional capability of building occupants is affected by age, gender and physical condition. There is considerable research available in the health literature and measures of obesity can be used as a predictor for walking capability which includes speed and fall potential. Unfortunately published data on the proportion of people with a BMI greater than 40 kg/m$^2$ and BMI as a function of age, gender and ethnicity was not specifically identified in much of the literature investigated.

The EvacuatioNZ Monte Carlo network evacuation model was used to investigate some of the functional effects on the evacuation of an exemplar high-rise building. Not surprisingly, the modelling suggests that total evacuations times will increase as populations age and trend towards higher proportions of obese occupants. These increases may be of the order of 5–8% when comparing 2006 and 2031 New Zealand scenarios and up to 20% when comparing the 1971 Canadian with the 2031 New Zealand scenario. Modelling occupants with a typical maximum design walking speed of 1.20 m/s gives smaller total evacuation times than when gender, age and BMI characteristics are included.

The EvacuatioNZ Monte-Carlo model provides a useful tool to investigate sensitivity of occupant variables but is limited in which aspects it can deal with. For example, the model does not currently account for the possibility of resting nor does it try to account for the potential reduction in movement due to the fear or occurrence of falls. The model also does not incorporate the effects of body size which might lead to blockages or reduced flows through plug effects. Door flows can be assigned by the user of the model (including the ability to specify a distribution function to door flows) but specific data with regard to the effect of increased body size has yet to be identified. It is hoped that further functionality can be incorporated in future versions of the EvacuatioNZ model and it would seem likely predicted total evacuation times would further reduce if resting, fall potential and increased body size are included.

The research suggests that the evacuation strategies of certain types of buildings (e.g. high-rise) may need to consider the egress capabilities of the likely current and future occupant population profiles. People with reduced stair descent (or ascent) ability cannot be analysed on their own but need to be considered in the context of the group. Evacuation planning can treat the vulnerable group as a mobility impaired person where they can be evacuated with assistance and/or use alternative means such as lifts. Thus evacuation system design needs to factor in the management strategy and other environmental factors.

## References


Adams, A.P.M., Galea, E.R., 2010, An experimental evaluation of movement devices used to assist people with reduced mobility in high rise building evacuations. In: Proc. Pedestrian Evacuation Dynamics, 8–10 March, National Institute of Standards and Technology, Gaithersburg, MD.

Al-Abdulwahab, S., 1999. The effects of aging on muscle strength and functional ability of healthy Saudi Arabian Males. Annals of Saudi Medicine 19 (3), 211–215.

APTA (Board of Directors, American Physical Therapy Association), 2009. Guidelines: Occupational health physical therapy: Evaluating functional capacity, American Physical Therapy Association, BOD 10-08-01-01.

Averill, J.D., Mileti, D., Peacock, R.D., Kuligowski, E.D., Groner, N.E., Proulx, G., Reneke, P.A., Nelson, H.E., 2007. Federal investigation of the evacuation of the world trade center on September 11, 2001. In: Waldau, N., Gattermann, P., Knoflacher, H., Schrekenberg, M. (Eds.), Pedestrian Evacuation and Dynamics, 3rd International Conference Proceedings, p.28-30, 2007, Springer Verlag, New York, pp. 1-12.

Ayis, S., Ebrahim, S., Williams, S., Juni, P., Dieppe, P., 2007. Determinants of reduced walking speed in people with musculoskeletal pain. Journal of Rheumatology 34, 1905–1910.

Basavarajappa, K.G., Ram, B., 2008. Population and migration, Statistics Canada, <http://www.statcan.gc.ca/pub/11-516-x/sectiona/4147436-eng.htm> (accessed November 2009).

Booth, F.W., Chakravarthy, M.V., Gordon, S.E., Spangenburg, E.E., 2002. Waging war on physical inactivity: Using modern molecular ammunition against an ancient enemy. Journal of Applied Physiology 93, 3–30.

Bruce, D.G., Devine, A., Prince, R.L., 2002. Recreational physical activity in healthy older women: The importance of fear of falling. Journal of American Geriatrics Society 50, 84–89.

Crowd Dynamics, 2007. Graphic levels of service. <http://www.crowdynamics.com>.

Dwyer, J., Flynn, K., 2006. 102 Min: The untold story of the fight to survive inside the twin towers. Times Books, ISBN 978-0-8050-8032-2.

Enright, P.L., Sherrill, D.L., 1998. Reference equations for the six-minute walk in healthy adults. American Journal of Respiratory and Critical Care Medicine 158, 1384–1387.

Fritz, S., Lusardi, M., 2009. Walking speed: the sixth vital sign. Journal of Geriatric Physical Therapy 32 (2), 2–5.

Fruin, J.J., 1987. Pedestrian planning and design, Revised Edition. Elevator World Inc., Mobile, Alabama.

Galea E.R., Hulse, L., Day, R., Siddiqui, A., Sharp, G., Shields, J., Boyce, K., Summerfield, L., Canter, D., Marselle, M., Greenall, P., 2008. The UK WTC9/11 evacuation study: an overview of the methodologies employed and some preliminary analysis. In: Proc. of the 4th Pedestrian and Dynamics (PED) Conference, February, 2008, University of Wuppertal, Germany.

Geraghty, E.M., Boone, J., 2003. Determination of height, weight, Body Mass Index and body surface area with a single CT scan image. Radiology, September 2003, 857–863.

Gwynne, S, M.V, Rosenbaum, E.R. 2008. Employing the hydraulic model in assessing emergency movement. Section 3, Chapter 13, The SFPE Handbook of Fire Protection Engineering (4th ed.). National Fire Protection Association, Quincy, MA.

Hamel, K.A., Kavanagh, P.R., 2004. Stair performance in people aged 75 and older. Journal of the American Geriatric Society 52, 563–567.

Haslam, R., Hill, D., Sloane, J., Howarth, P., Wavell, K.B., 2006. *Behaviour and the safety of older people on stairs*. In Haslam, R., Stubbs, D. (Eds.), Understanding and Preventing Falls, Taylor and Francis, pp. 209–234.

He, X.Z., Baker, D.W., 2004. Body mass index, physical activity, and the risk of decline in overall health and physical functioning in late middle age. American Journal of Public Health 94 (9), 1567–1573.

Hills, A.P., Byrne, N.M., Wearing, S., Armstrong, T., 2006. Validation of the intensity of walking for pleasure in obese adults. Preventive Medicine 42, 47–50.

Hue, O., Simoneau, M., Marcotte, J., Berrigan, F., Dore, J., Marceau, P., Marceau, S., Tremblay, A., Teasdale, N., 2007. Body weight is a predictor of postural stability. Gait and Posture 26, 32–38.

Hulens, M., Vansant, G., Claessens, A.L., Lysens, R., Muls, E., 2003. Predictors of 6-minute walk test results in lean, obese and morbidly obese women. Scandinavian Journal of Medicine and Science in Sports 13, 98–105.

Kady, R., Davis, J., 2008. The effect of occupant characteristics on crawling speed in evacuation. Fire Safety Journal 44, 451–457.

Kang, H.G., Dingwell, J.B., 2008. Effects of walking speed, strength and range of motion on gait stability in healthy old adults. Journal of Biomechanics 41, 2899–2905.

Ko, S.Y., Spearpoint, M.J., Teo, A., 2007. Trial evacuation of an industrial premises and evacuation model comparison. Fire Safety Journal 42 (2), 91–105.

Leiper, C.I., Cralk, R.L., 1991. Relationships between physical activity and temporal-distance characteristics of walking in elderly women. Physical Therapy 71 (11), 791–803.

Lopes, K.T., Costa, D.F., Santos, L.F., Castro, D.P., Bastone, A.C., 2009. Prevalence of fear of falling among a population of older adults and its correlation with mobility, dynamic balance, risk and history of falls. Rev Bras Fisiotier 13 (3), 223–229.

Lord, J., Meacham, B., Moore, A., Fahy, R., Proulx, G., 2005., Guide for evaluating the predictive capabilities of computer egress models. NIST GCR 06-886, National Institute of Standards and Technology, Gaithersburg, MD, USA, pp. 102.

Lord, S., Sherrington, C., Menz, H.B., 2006. Ageing and falls. In: Haslam, R., Stubbs, D. (Eds.), Understanding and Preventing Falls, Taylor and Francis, pp. 89–114.

MacLennan, H.A., Faruk, M., Ormerod, M., Newton, R., 2008. Will current emergency evacuation systems be accessible and usable in 2030?. In: Finch. E. (Ed.), Proc. CIB W070 Conference in Facilities Management, Healthy and Creative Facilities, 16–18 June 2008, Heriot Watt University, Edinburgh, p. 149–158.

MacLennan, H.A., 2010. The risk of people associated with the descent of multiple flights of stairs – an inclusive perspective. In: International Stair Safety Workshop, 16th April 2010, Health and Safety Laboratories, Buxton, UK.

MacLennan, H.A., 2011. The risk of people descending multiple flights of stairs in high rise office buildings as part of their job description. PhD Programme in progress, University of Salford, UK.

Mhurchu, C.N., Turley, M., Stefanogiannis, N., Lawes, C.M.M., Rodgers, A., Hoorn, S.V., Tobias, M., 2004. Mortality attributable to higher-than-optimal body mass index in New Zealand. Public Health Nutrition 8 (4), 402–408.

Ministry of Health, 2004. The health of New Zealand: Total population, Wellington, New Zealand.

Ozanne-Smith, J., Guy, J., Kelly, M., Clapperton, A., 2008. The relationship between slips trips and falls in the design and construction of buildings. Report No. 281, Monash University Accident Research Centre.

Pauls, J., 1987. Calculating evacuation times for tall buildings. Fire Safety Journal 12, 213–236.

Pauls, J., 2007. Design issues within the egress stairway enclosure. In: Proc AEI Symposium on Egress Stairs in High-Rise Buildings. Architectural Engineering Institute of the American Society of Civil Engineers, New York.

Peacock, R.D., Averill, J.A., Kuligowski, E.D., 2009. Stairwell evacuation from buildings: What we know we don't know, NIST Technical Note 1624, National Institute of Standards and Technology, Gaithersburg, MD.

Pires, S.R., Oliveira, A.C., Parreira, V.F., Britto, R.R., 2007. Six-minute walk test at different ages and body mass indexes. Revista Brasileira de Fisioterapia 11 (2), 131–134.

Pitt-Catsouphes, M., Smyer, M.A., 2006. How old are today's older workers?, Issue Brief 04, The Center on Aging and Work, Boston College, Chestnut Hill, MA.

Proulx, G., Benichou, N., Hum, J.K., Restivo, K.N., 2007. Evaluation of the effectiveness of different photoluminescent stairwell installations for the evacuation of office building occupants. Report IRC-RR-232, National Research Council of Canada, Ottawa.

Proulx, G., 2008. Evacuation time. Section 3, Chapter 12, The SFPE Handbook of Fire Protection Engineering (4th ed.). National Fire Protection Association, Quincy, MA.

Reeves, N.D., Spanjaard, M., Mohagheghi, A.A., Baltzopoulos, V., Maganaris, C.N., 2008. The demands of stair descent relative to maximum capacities in elderly and young adults. Journal of Electromyography and Kinesiology 18, 218–227.

Smith, R.A., 1995. Density, velocity and flow relationships for closely packed crowds. Safety Science 18, 321–327.

Spearpoint, M.J., 2009. Comparative verification exercises on a probabilistic network model for building evacuation. Journal of Fire Sciences 27 (5), 409–430, doi: 10.1177/0734904109105373.

Statistics New Zealand, 2009a. Census of population and dwellings. <http://www.stats.govt.nz/>, (accessed November 2009).

Statistics New Zealand, 2009b. Population estimates and projections. <http://www.stats.govt.nz/methods_and_services/TableBuilder/population-projections-tables.aspx>, (accessed November 2009).

Stel, V.S., Pluijm, S.M.F., Deeg, D.J.F., Smit, J.H., Bouter, L.M., Lips, P., 2003. A classification tree for predicting recurrent falling in community dwelling older persons. Journal of the American Geriatrics Society 51, 1356–1364.

World Health Organisation, 2009. Global database on Body Mass Index. (accessed November 2009).