ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

Evaluating Staircase Safety Using BIM-based Virtual Simulation: Focusing on the Elderly in the Republic of Korea

Hyuncheul Yang[1], Kwangbok Jeong[2], Sohyun Kim[3], Jaewook Lee[4]*

[1] *Department of Architectural Engineering, Sejong University, Seoul, 05006, Republic of Korea.* E-mail: cheori87@gmail.com
[2] *Deep Learning Architecture Research Center, Department of Architectural Engineering, Sejong University, 209, Neungdong-ro, Gwangjin-gu, Seoul 05006, South Korea.* E-mail: kbjeong7@sejong.ac.kr
[3] *Department of Architectural Engineering, Sejong University, Seoul, 05006, Republic of Korea.* E-mail: thgus960221@sju.ac.kr
[4] *Deep Learning Architecture Research Center, Department of Architectural Engineering, Sejong University, 209, Neungdong-ro, Gwangjin-gu, Seoul 05006, South Korea.* E-mail: jaewook@sejong.ac.kr

Abstract: As the population is aging, accidents involving elderly people are also increasing (2014:11,667 persons; 2018: 11,797 persons). In the case of the elderly population, falling accidents are the primary direct or indirect causes of death; in particular, they face an elevated risk of staircase falls. This study proposes a method of evaluating the safety of staircases using Building Information Modeling (BIM)-based virtual simulation. By making a virtual user with the behavioral characteristics of the elderly respond to a staircase in a BIM model, its safety performance can be evaluated. The evaluation criteria were derived from regulations, elements, and characteristics relevant to the safety of staircases. To validate the proposed method, safety evaluation tests were simulated on actual staircases. The evaluation result of the test simulation shows the safety scores of 1.97 points for the elderly user and 2.95 points for the average male adult user against a required safety score of a minimum of 2 points. That is, safety is relative to users as the safety of the same staircase can be different depending upon the different behavioral characteristics of users. The study suggests that the risk of staircase-related fall accidents to the elderly can be reduced by improving staircase designs through the proposed method.

Key words: Building Information Modeling, Staircase safety, Elderly people, Behavioral characteristics, Pre-occupancy evaluation

1. INTRODUCTION

In 2018, the safety accident fatalities in South Korea accounted for 9.38% of the total fatalities, which is 1.49 times higher than the average fatalities (6.3%) recorded by the Organization for Economic Co-operation and Development (OECD). In addition, 42.07% (11,797) of the total safety accident fatalities involved elderly individuals (aged 65 and above) [1]. In terms of accident type, fall or falling accidents (hereinafter referred to as fall accidents) of the elderly are increasing by more than 35% per year, as compared to the increase in overall accidents of approximately 15%

per year. In addition, the proportion of serious injury accidents that require more than one month of treatment in hospitals and clinics was 3.5 times higher for the elderly (13%) than other age groups (3.7%). Among all fall accidents, 82.1% occurred in houses, medical service facilities, and welfare and elderly care facilities, indicating that most such accidents occur in living spaces that cater to the elderly [2].

In particular, staircases for vertical movement in living spaces pose a high risk of fall accidents. In many studies conducted to prevent fall accidents, risk factors and improvements related to the physical components of staircases have been proposed. However, most of these studies focused on appropriate staircase dimensions under controlled experimental environments [3-6], but excluded the diverse behavioral characteristics of users in relation to the physical conditions of real buildings. Therefore, their findings may be limited for preventing actual fall accidents of the elderly in buildings.

Because current staircase designs only meet relevant regulations that define minimum criteria for safety and often fail to meet even basic standards [2], to reduce fall risks, the safety of staircases in buildings should be improved through performance evaluation. A representative method for evaluating the spatial performance of a building is Post-Occupancy Evaluation (POE), in which users evaluate the space by directly experiencing it [7]. Although POE is the most accurate method for evaluating the performance of actual space, evaluation can only be done after the construction of the space. Thus, considerable cost and time are necessary to implement improvements from POE results in a space that is being used, and, in some cases, modifications might be impossible [8]. One method to overcome the limitation of POE is Pre-Occupancy Evaluation (PrOE) [9], which enables preliminary performance evaluation in virtual space prior to the physical construction of a building [10]. The PrOE can improve users' spatial satisfaction by evaluating the design of a space in advance through virtual simulation and incorporating evaluation results during the design stage.

In previous PrOE studies, however, evaluations were generally performed based on users with average characteristics (e.g. adult males in their 20s). In such cases, spaces such as childcare facilities, welfare facilities for the elderly, and facilities for people with disabilities could not be accurately evaluated based on the behavioral characteristics of specific users. To address this problem, it is important to carefully define the virtual user, who can be classified and created with specific behavioral characteristics based on particular biological and cultural elements [8]. However, using virtual users alone in the concept verification stage is still not sufficient. Accordingly, in this study, a virtual user was used along with an evaluation model to conduct an evaluation simulation of staircases with high fall accident risks based on the cultural and physical characteristics of elderly subjects. The results were used to propose a method for evaluating the safety of staircases in elderly facilities using Building Information Modeling (BIM)-based virtual space evaluation simulation to find accurate PrOE and contribute to the design improvement of facilities for the elderly.

2. IMPLEMENTATION OF VIRTUAL ELDERLY USERS BASED ON BEHAVIORAL CHARACTERISTICS

2.1. Implementation of virtual user based on behavioral characteristics

To perform virtual simulation for safety accident prevention, virtual users representing humans must be used to evaluate the space. These users can be given biological and cultural attributes matching those of humans according to the evaluation space and purpose [8]. For this study, the average human body size information for individuals aged 65–69 years was obtained from data from the "Korean Human Body Size Survey [11]" by the Korean Agency for Technology and

Standards and similar studies. Samples to represent physical characteristics that are closely related to staircase fall accidents by the elderly were then extracted.

In deriving the components applied to the virtual users in the virtual space simulations, we focused on biological elements, which are particularly essential in modeling fall accidents by elderly individuals because the main cause of such accidents is aging. As an actual behavior is affected by these biological elements [11], determining them was the first step in defining the virtual users. The components of the virtual users also had to be defined in terms of elements affecting spatial evaluation. Many of these had been developed in previous studies on behavioral psychology theory, which posits that individuals determine their behavior in space depending on cultural elements [12-14]. Table 1 summarizes the derived behavioral characteristic components of the elderly virtual users.

Table 4. Behavioral characteristic components of virtual elderly users

Class 1	Class 2	Class 3	Codes
Biological element	Gender	Male	B1
	Age	65–69	B2
	Physical characteristics	Stature	B3
		Foot length	B4
		Hip joint moment	B5
		Biacromial breadth	B6
		Vision	B7
Cultural element	Walking direction	Right	C1
		Left	C2

2.2. Establishment of evaluation criteria of and equations of staircase fall accidents

Staircase safety evaluation criteria were defined using the behavioral characteristics of elderly users along with the staircase-related regulations and dimensions. To apply the evaluation criteria in the simulations, an appropriate mathematical formulation was defined for each evaluation element. A total of nine mathematical formulations (Eq.1 – Eq. 9) for evaluating eight elements (i.e., E1-E8) for physical characteristics and one element for walking direction (i.e., E9) were defined (refer to Table 2). The Eq.1-Eq.8 developed by Yang et al. (2017) [15] were used to evaluate the evaluating eight elements (i.e., E1-E8). Eq.9 is developed to evaluate the user's walking direction as a cultural characteristic, which is either right-side walking (Korea, USA, etc.) or left-side walking (Australia, New Zealand, etc.). To reduce the risk of falling accidents, handrails should be on the side where the user descends. In general, in a stairwell, since handrails are not installed on the wall side, but installed only at the center, the safety of a staircase varies depending on the correlation of the user's walking direction, staircase direction, and handrail presence. For example, when a right-side walking user descends a left-turn (from lower to upper floor) staircase, the user can hold the handrails at the center, whereas, in the case of a right-turn staircase, the descending user cannot hold the handrails on the wall side. Therefore, the safety score of the left-turn staircase is relatively higher than the right-turn staircase (i.e. the left-turn staircase is safer (safety score: e than the right-turn one (safety e 1.33) for the right-side walking user) (refer to Table 3).

In addition, the evaluation equations were developed so that safety scores from 0–4 points could be calculated using linear interpolation, a method for linearly estimating values between given endpoint values along with a straight-line distance. For example, for step height values of 15.9 and

16 cm, a one-point score difference for the height difference of 0.1 cm is not reasonable. Therefore, the safety scores are calculated to yield a difference of ± 1 point from the minimum safety score of 2 points for every ±10% measurement change of the evaluation element. Here, the safety score of each evaluation element should be 2 points at least for the user to be safe with the element. In addition, weights are assigned to the staircase components for which the installation criteria are different between elderly facilities and general facilities in consideration of the differences in motor ability between the elderly and adult users.

Table 5. Staircase safety evaluation elements

No.	Evaluation elements	Equations
1	E1: Height of handrail	$Eq.1 = \frac{4*\frac{EM1}{B3*0.55*10}-3.2}{0.4}$
2	E2: Width of tread	$Eq.2 = \frac{4*\left(\frac{EM2-60}{B4*0.9+60}*W1\right)-3.2}{0.4}$
3	E3: Height of riser	$Eq.3 = \frac{-4*\left(\frac{EM3}{\frac{18*B5+768.06}{3.52}}\right)+4.8}{0.4}$
4	E4: Slope	$Eq.4 = \frac{-4*\left(\frac{EM4}{\operatorname{atan}\left(\frac{\frac{18*B5+768.06}{3.52}}{B4*0.9+60}\right)*\left(\frac{180}{\pi}\right)}*W2\right)+4.8}{0.4}$
5	E5: Width of staircase	$Eq.5 = \frac{4*\left(\frac{EM5}{B6*2.5}*W3\right)-3.2}{0.4}$
6	E6: Height of landing	$Eq.6 = \frac{-4*\left(\frac{EM6-EM7}{1800}*W4\right)+4.8}{0.4}$
7	E7: Width of landing	$Eq.7 = \frac{4*\frac{EM8}{1200}-3.2}{0.4}$
8	E8: Illuminance	$Eq.8 = \frac{4*\left(\frac{EM9}{\frac{-50*B7+135}{0.7}}*W5\right)-3.2}{0.4}$
9	E9: Walking direction	$Eq.9 = 4*\frac{Cn+EM10+EM11}{3}\ (n:1,2)$

Note. EM1 is the height of the handrails of the BIM model; EM2 is the tread width of the BIM model; EM3 is the riser height of the BIM model; EM4 is the stair angle of the BIM model; EM5 is the staircase width of the BIM model; EM6 is the floor of the BIM model; EM7 is the landing height of the BIM model; EM8 is the landing width of the BIM model; EM9 is the illuminance of the BIM model; EM10 is handrail presence of the BIM model; EM11 is staircase direction; B3 is the height of the virtual user; B4 is the foot size of the virtual user; B5 is the hip joint moment of the virtual user; B6 is the shoulder width of the virtual user; B7 is the visual (eyesight) characteristic of the virtual user; Cn is user walking direction of the virtual user (i.e., C1: right-side and C2: left-side); W1 is the weighting factor for the tread width; W2 is the weighting factor for stair angle evaluation; W3 is the weighting factor for width in the staircase evaluation; W4 is the weighting factor for evaluating the landing height; W5 is the weighting factor for illuminance evaluation.

Table 6. Evaluation of walking direction

Walking direction	Staircase direction (from lower to upper floor)	Handrail presence	Safety score
Right-side	Left-turn	O	4
Right-side	Right-turn	X	1.33
Left-side	Left-turn	O	4
Left-side	Right-turn	X	1.33

Note. 'O' means that the user can hold handrail at the center when the user goes down the stairs; 'X' means that the user can not hold handrail at the center when the user goes down the stairs.

3. VIRTUAL SIMULATION FOR EVALUDATING THE SAFETY OF STAIRCASE

3.1. Determination of the simulation case

In the test case applied in this study, an evaluation simulation was performed using the model of an actual elderly facility. An actual elderly facility located in Incheon of South Korea (i.e., total floor area: 299.88 m2) was selected for the spatial model used for staircase safety evaluation simulation.

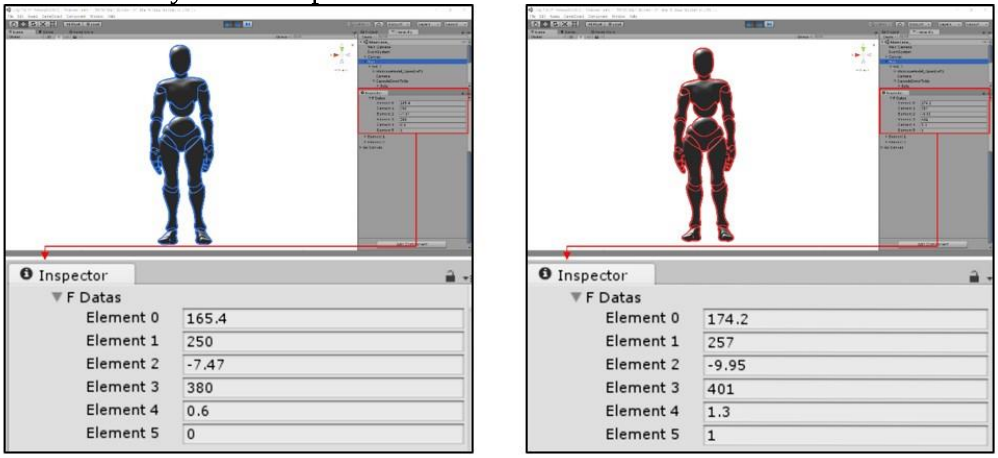
3.2. Implementation of spatial model and user model

In the simulation, an elderly virtual user and an adult virtual user in his 20s were implemented to examine the effects of biological elements on behavioral characteristics. To examine the effects of cultural elements on a given space model, evaluation simulation was performed by implementing the elderly virtual user on different types of the staircase (i.e., staircase turning directions). As a comparison target, an adult in his 20s was selected as such subjects are commonly used as benchmarks in virtual simulation evaluation, are generally the most physically active age cohort, and tend to have the excellent motor ability.

To create the virtual space, a BIM model was prepared using Autodesk Revit (ver. 2019). Autodesk 3DS MAX (ver. 2020) was used to implement the virtual users, and Unity Game Engine (ver. 5.6.1f1) was used to implement the evaluation simulation. The property information was entered to the virtual users using Unity Game Engine, while spatial information from the BIM model was imported to the evaluation equations. A virtual simulation was then performed to validate the proposed method of evaluating staircase safety using virtual users with behavioral characteristics. As they would be required to climb up and down the stairs in the simulation, the geometry of the users was modeled by embedding a human skeleton to enable movement of the joints in a human-like manner and then inserting animation to obtain the final virtual users.

3.3. Implementation of staircase safety evaluation

Figure 1 shows the input screen for assigning virtual user behavioral characteristics. For the staircase safety evaluation simulation, two virtual users (i.e., an elderly user (refer to (a) in Figure 1), and an adult user (refer to (b) in Figure 1), were implemented. The two users had the same geometry but had different behavioral characteristic elements (i.e., six biological elements and one cultural element for a residential area) as implemented in Unity Game Engine. After importing the space model into the evaluation simulation, the virtual users experienced the space to evaluate the safety of the staircase via the evaluation equations presented in Section 2.2, which were coded and implemented so that they could be processed via simulation.



Element 0 165.4
Element 1 250
Element 2 -7.47
Element 3 380
Element 4 0.6
Element 5 0

Element 0 174.2
Element 1 257
Element 2 -9.95
Element 3 401
Element 4 1.3
Element 5 1

(a) Behavioral characteristics of the elderly user (b) Behavioral characteristics of the adult user

Figure 7. Input screen for assigning virtual user behavioral characteristics

3.4. Simulation results of safety evaluation of staircase

In the staircase safety evaluation simulation, a comparison test was conducted to evaluate staircase safety for the elderly and adult virtual users in terms of their physical differences and cultural characteristics. The simulation for the elderly virtual user was also altered by varying the staircase turn direction to reflect cultural differences (i.e., walking direction) and validate the evaluation. The final safety scores for the elderly and adult users were 1.97 and 2.95 points, respectively. This means that the target staircases are less safe for the elderly user than the adult user. Despite the application of the same staircase model, the evaluation results were different because of the different behavioral characteristics (refer to Table 4).

Table 7. Results of evaluation simulation reflecting differences in behavioral characteristics

Category	Elderly user (walking direction: right)	Adult user (walking direction: right)
Height of handrail	1.89	1.39
Width of tread	0	0
Height of riser	3.11	3.91
Slope	2.34	3.03
Width of staircase	0	3.46
Height of landing	3.71	4
Width of landing	2.75	2.75
Illuminance	0	4
Walking direction	4	4
Safety score	1.97	2.95

The difference in walking direction as a cultural characteristic was evaluated for the same elderly virtual user. Using a right-turn staircase resulted in a slightly higher safety score than using a left-turn staircase (1.98 versus 1.68 points, respectively), reflecting the convention in the Republic of Korea, where keeping to the right side is the standard (refer to Table 5). In the evaluation of the staircase model based on the behavioral characteristics of the elderly user, the minimum satisfaction score of 2 out of 4 points could not be reached. However, the evaluation simulation allowed us to identify and assess problems objectively to improve the safety performance of the staircases.

Table 8. Results of evaluation simulation reflecting behavioral differences

Category	Elderly (staircase direction: left)	Elderly (staircase direction: right)
Height of handrail	1.89	1.89
Width of tread	0	0
Height of riser	3.11	3.11
Slope	2.34	2.34
Width of staircase	0	0
Height of landing	3.71	3.71
Width of landing	2.75	2.75
Illuminance	0	0
Walking direction	1.33	4
Safety score	1.68	1.98

4. Conclusion

A staircase safety evaluation method and a behavioral characteristic implementation for elderly individuals were developed through the assessment in virtual space of a virtual user with the behavioral characteristics of an elderly subject. The results confirmed the possibility of evaluating the safety of staircase models and using the results to modify design elements in advance. The test case verification applied the following procedures and obtained the following conclusions. First, the behavioral characteristics of the users were the main elements of the evaluation. The elements related to staircase fall accidents were identified through previous studies and theoretical investigation. Evaluation criteria were prepared by analyzing the relationship between these elements and behavioral characteristics. Second, the results of safety evaluation simulations performed within a given space differed based on the respective behavioral characteristics of elderly and adult individuals. The evaluation possibility by assigning behavioral characteristics to virtual users was confirmed. Therefore, it was confirmed that it is possible to apply PrOE based on behavioral characteristics and that such characteristics can be important criteria for evaluation.

The study, however, had several limitations. First, the staircase model was evaluated using only one virtual user at a time, making the results difficult to extrapolate to cases in which multiple users use a space. It was also difficult to evaluate all elements related to fall accidents owing to limitations on the available data. In future work, therefore, it will be necessary to construct spatial evaluation models that can be implemented for multiple virtual users, to develop a systematic classification and definition of fall accident evaluation elements, and to derive a big data preparation plan for the collection, management, and analysis of safety accident data.

Although the virtual simulations conducted in this study were limited to staircase safety evaluation, evaluation criteria can be added to accommodate other evaluation purposes and spaces using the proposed method. By doing so, it will be possible to evaluate an entire elderly facility, which can contribute significantly to safety improvements through prior safety evaluation during the design phase of the facility.

ACKNOWLEGEMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MIST; Ministry of Science and ICT) (NRF-2020R1A4A2002855, NRF-2021R1F1A1049692).

REFERENCES

[1]KOSIS(Korean Statistical Information Service). Available online: http://kosis.kr/ (Jan. 02. 2020).

[2]KCA(Korea Consumer Agency). Available online: http://ciss.go.kr/www/selectBbsNttView.do?key=187&bbsNo=84&nttNo=29761&searchCtgry&searchCnd=all&searchKrwd&pageIndex=1&pageUnit=10&integrDeptCode (Jan. 05. 2020).

[3] S. Yoon, The Effect of Stair Depth on Ground Reaction Force Parameters - Asymmetric and Variability Indices -, Korean journal of sport biomechanics 2008, 18(1), pp. 169–178. DOI: https://doi.org/10.5103/KJSB.2008.18.1.169

[4] Y. Kim, A Study about Physical Change According to the Difference of Stair Height in going up Stairs -Focus on the changing of pulse and blood Pressure-, Journal of the architectural institute of Korea : Planning & design 2003, 19(4), pp. 57–66.

[5] Y. Kim, A Study on the Design of Optimum Dimension of Staircase -Focused on the Minimum Dimension of Riser, Tread and Slope for Safety on Staircase-, Journal of the Korean Housing Association 2003, 14(5), pp. 105–116.

[6] K. Chung, J. Chung, A Study on the Safety of Stairs for Multi-family Housing, Journal of The Architectural Institute of Korea Planning & Design 2000, 16(12), pp. 47–53.

[7] W. Preiser, (Ed.). Building evaluation, 2nd ed.; Springer Science & Business Media: Berlin, Germany, 2013; pp. 289-327. DOI: https://doi.org/10.1007/978-1-4899-3722-3

[8] S. Shin, S. Jeong, J. Lee, S. Hong, S. Jung, Pre-Occupancy Evaluation based on user behavior prediction in 3D virtual simulation. Automation in Construction 2017, 74, pp. 55–65. DOI: https://doi.org/10.1016/j.autcon.2016.11.005

[9] Y. Kalay, Architecture's new media: Principles, theories, and methods of computer-aided design, 1st ed, MIT Press: Massachusetts, United States of America, 2004; pp. 295–375.

[10] H. Alzoubi, R. F. Bataineh, Pre-versus post occupancy evaluation of daylight quality in hospitals, Building and Environment 2010, 45(12), pp. 2652–2665. DOI: https://doi.org/10.1016/j.buildenv.2010.05.027

[11] Statistics Korea. Available online: https://sizekorea.kr (Jan. 02. 2020).

[12] D. Stokols, Origins and directions of environment-behavioral research. In Perspectives on environment and behavior, Springer: Boston, United States of America, 1977; pp. 5–36.

[13] R. D. Gastil, The determinants of human behavior. American Anthropologist 1961, 63(6), 1281-1291.

[14] E. Goffman (1963). Behavior in public places: Notes on the social organization of gatherings. New York: Free Press.

[15] H. Yang, S. Na, D. Kim, J. Lee, Evaluation of staircase accidents using 3D virtual simulation based on behavioral characteristics of the elderly, Journal of Korean Institute of Building Information Modeling 2017, 7(4). DOI: https://doi.org/10.13161/kibim.2017.021