FUNCTIONAL FOOTWEAR DESIGN FOR PREVENTING FALLS IN THE ELDERLY: A SYSTEMATIC RESEARCH BASED ON FAULT TREE ANALYSIS

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ABSTRACT. The purpose of this research is to improve the elderly's footwear for preventing falls in walking. The design method of the footwear for the elderly was proposed based on fault tree analysis (FTA). There were four phases for improving the footwear. At first, the fault tree diagram was built by determining the causes of the elderly falling, literature review and user interview were applied at this phase. Then, both qualitative and quantitative analyses were conducted. The minimal cut sets of the elderly falls were identified. Besides, seven core risk factors were proven as strong or moderate influences for the falling issues, and which are related directly or indirectly to the elderly's footwear. Finally, the footwear optimizations were made, and the seven core risk factors were mainly considered in the design process. The proposed design method provided a series of specific steps to help to define the practical causes of the elderly falling. The improvements of the footwear were made reasonable in that way, as well as enabled an improved experience for the elderly users.

KEY WORDS: elderly, functional footwear, falls prevention

DESIGN FUNCȚIONAL DE ÎNCĂLȚĂMINTE PENTRU PREVENIREA CĂDERILOR LA VÂRSTNICI: O CERCETARE SISTEMATICĂ BAZATĂ PE METODA ARBORELUI DE DEFECTARE

REZUMAT. Scopul acestei cercetări este de a îmbunătăți încălțămintea pentru persoanele în vârstă cu scopul de a preveni căderile în timpul mersului. Metoda de proiectare a încălțămintei pentru vârstnici a fost propusă pe baza metodei arborelui de defectare. Îmbunătățirea încălțămintei s-a desfășurat în patru faze. La început, s-a realizat diagrama arborelui de defectare prin determinarea cauzelor căderii în cazul vârstnicilor; în această fază s-a studiat literatura de specialitate și s-au realizat interviuri cu utilizatorii. Apoi, au fost efectuate atât analize calitative, cât și cantitative. S-au identificat seturile de evenimente primare care conduc la căderi. În plus, șapte factori de risc fundamentali s-au dovedit a fi influențe puternice sau moderate pentru căderi, aceștia fiind corelați direct sau indirect cu încălțămintea purtată de vârstnici. În cele din urmă, s-a optimizat încălțămintea, iar cei șapte factori de risc fundamentali au fost luați în considerare în procesul de proiectare. Metoda de proiectare propusă a oferit o serie de etape specifice pentru a facilita definirea cauzelor practice ale căderii la vârstnici. S-au adus îmbunătățiri rezonabile încălțămintei, permițând astfel o experiență mai bună pentru utilizatorii în vârstă.

CUVINTE CHEIE: vârstnici, încălțăminte funcțională, prevenirea căderilor

LA CONCEPTION FONCTIONNELLE DE CHAUSSURES POUR LA PRÉVENTION DES CHUTES CHEZ LES PERSONNES ÂGÉES : UNE RECHERCHE SYSTÉMATIQUE BASÉE SUR LA MÉTHODE D'ANALYSE DE L'ARBRE DE DÉFAILLANCES

RÉSUMÉ. L'objectif de cette recherche est d'améliorer les chaussures des personnes âgées afin de prévenir les chutes lors de la marche. La méthode de conception de chaussures pour personnes âgées a été proposée sur la méthode d'analyse de l'arbre de défaillance. L'amélioration de la chaussure s'est déroulée en quatre phases. Au départ, le schéma de l'arbre de défaillance a été réalisé en déterminant les causes de la chute chez les personnes âgées ; dans cette phase, la littérature a été étudiée et des entretiens ont été menés avec les utilisateurs. Ensuite, des analyses qualitatives et quantitatives ont été réalisées. Les coupes minimales menant aux chutes ont été identifiés. De plus, il a été démontré que sept facteurs de risque clés ont une influence forte ou modérée sur les chutes, qui sont directement ou indirectement liées aux chaussures portées par les personnes âgées. Enfin, les chaussures ont été optimisées et les sept facteurs de risque clés ont été pris en compte dans le processus de conception. La méthode de conception proposée prévoyait un certain nombre d'étapes spécifiques pour faciliter la définition des causes pratiques des chutes chez les personnes âgées. Des améliorations raisonnables ont été apportées aux chaussures, permettant une meilleure expérience pour les utilisateurs plus âgés.

MOTS CLÉS : personnes âgées, chaussures fonctionnelles, prévention des chutes

INTRODUCTION

Falls among the elderly have widely drawn attention; WHO revealed a fact that approximately 684,000 people fall-related die every year worldwide, as well as people aged over 60 are more likely to take a higher risk [1]. Almost all falls happen when the body is in motion, and footwear is considered a significant risk. In recent years, there have been some footwear designs made to minimize the risk of falling. For example, Cheng *et al.* designed the smart shoes with tracking and the shoes were 3D printed to fit the deformation of the elderly's foot [2]; Aboutorabi *et al*. designed a vibrating system in the sole of the footwear to enhance the postural stability for the elderly [3]. Most solutions were individually targeted and technologies applied. However, WHO also indicated the risk of elderly falls could be caused by various reasons, including physical, psychological modifications of aging, and the external impacts [1]. However, present design concepts were based on less comprehensive consideration. Thus, it is necessary to investigate

elderly falls in a comprehensive manner and propose an integrated design.

Fault tree analysis (FTA) is a significant method for a comprehensive investigation. As a practical technique, FTA can be applied to determine relevant potential causes of the system failure in a deductive way, which would be helpful for enhancing the reliability and safety of the system. FTA has been widely used for predicting possible equipment failure, planning maintenance, and evaluating risks. One typical research from the department of Kaiserslautern University, is that fault tree construction was applied to analyze and improve the safety of ambient assisted living for the elderly [4]. FTA allows the designer to investigate how module defeats lead to system undesired events happened in the context of the environment and operation, and then the results would help to improve the design [5]. In this study, a fault tree is proposed to identify the causes of elderly falls from both internal and external aspects. External factors include unsuitable shoes and environmental effects. Internal factors include psychological and physiological causes. Falls among the elderly as an undesirable failure in the fault tree and which is broken down into every basic fault inputs. All basic fault inputs are analyzed in terms of both quality and quantity. The results of FTA are presented as an expose of their interrelations and an importance ranking, and the results are applied in the footwear design comprehensively.

This paper aims to evaluate the ultimate causes of elderly falls by the method of FTA, and thus propose an integrated solution of elderly functional shoes. The logic deduction of causes would be conducted and represented on the fault tree diagram. The diagram shows the root of the problems, and which helps the designer to exam the ultimate causes of falls. Based on this, FTA is applied to the footwear design for qualitative and quantitative analysis of elderly falls. After the critical causes of failure are identified, the solutions would be proposed with shoes toward those causes. This study will give a reasonable solution to elderly falls as well as a useful reference for the optimization of footwear design.

METHODOLOGY

Fault Tree Analysis

The fault tree model is a graphical way that demonstrates how failures are caused through logical decomposing of the undesired event into basic events. It allows the designer to analyze the product in the context of the user, environment, and operation to figure out entire reliable causes why the undesired event happen [5]. The faults could connect to the components defeats, human faults, or other environmental problems. Therefore, a fault tree can be applied to present the logical interrelationships between basic events and the undesired event that they led. Each event of the tree is connected by the gates as a logic flow. The top event is the output of the tree, and basic events are the inputs of the tree.

However, considering a complex system investigation, it could be plenty of events and combinations. The fault tree can not only draw quantitative results, but also qualitative results. Quantitative measurements are applied to calculate the failure probability of the basic events. Based on the measurements, the basic events would be sorted by correlation, from greatest to least.

Thus, FTA is applied in this paper, aims to determine the causes of elderly falls in the context, and helps to improve the footwear design for the elderly to prevent from falling.

Fault Tree Construction for Elderly Falls

This study presents an optimum footwear design for the elderly to prevent falling based on analyzing a fault tree. Concerning relevant factors of elderly falls, the structure and materials of shoes would be enhanced to more accommodate the elderly's behavior and minimizing the falling risk. Figure 1 presents the flow of developing and analyzing the fault tree of elderly falls, which are described in the following subsections.

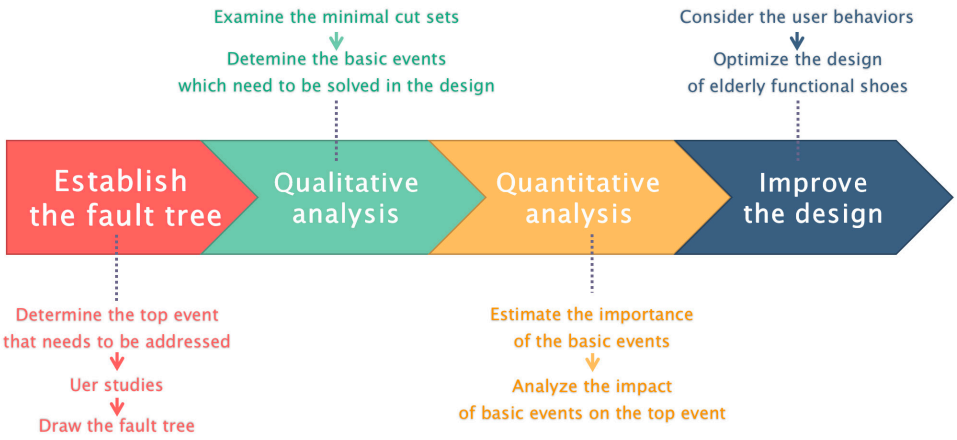

Figure 1. Research method flow

Establish the Fault Tree

As shown in figure 1, there are three steps to build the fault tree model.

At first, it is to choose the top event carefully. The top event as an undesired event is deduced in the fault tree diagram to figure out causes. The top event could not be overall or too specific due to the investigation must be manageable and wide viewed [5]. From the above considerations, falls among the elderly are a suitable undesired event for fault tree analysis.

The second step of this stage is to fully understand the causes of elderly people's falls. The literature review and interview were applied at this step. Literature review is mainly focused on the risk factors for elderly falls, categorizing personal specific and extrinsic reasons [6]. Personal reasons involve physical and psychological factors [7]. Extrinsic reasons refer to environmental factors such as poor lighting, slippery staff, as well as unsuitable footwear [8]. A detailed illustration of the risk factors would be shown in the next section of the results and discussion. Thus, based on the results of the literature review, the questionnaire is designed, and interviewed 20 old people. The questionnaire is given in the appendix, and Informed consent which were signed by all study participants was attached. Besides, the results would be further discussed in the results section.

After deep learning of elderly falling causes, the fault tree model could be constructed by the deductive method. The fault tree model is constituted by symbols that represent different incidents. The top event is in the uppermost rectangle, followed by the intermediate events which are also in the rectangle, and the basic events are in the circle at the bottom. The intermediate events are those faults that happened and can be broke down into further factors, and the basic events describe those faults which require no more decomposition. However, there is one kind of undeveloped event which is described by the diamond that would not be decomposed further since the unavailable information is related. All events are connected by the gates in the fault tree. There are normally two types of gates, including the AND-gate and the OR-gate. The OR-gate is applied to represent that only if one of the lower events occurs would lead the upper event occurs. The AND-gate is applied to represent that only if all the lower events occur would lead to the upper event occurs. The fault tree model of elderly falls is produced and would be introduced in the section of results.

Qualitative Analysis of the Fault Tree

The purpose of qualitative analysis is to identify the minimal cut sets of the fault tree, which are all the unique combinations of basic events that cause the top event failure. In other words, if one of the combinations fails, the system will fail. However, not all factors can be controlled and optimized in the footwear design, especially some external factors such as loss of concentration [6]. For those non-repairable factors, there are no more considerations in this footwear design. The more specific factors will be discussed in the next section of the results.

Thus, there are two steps to qualitative analysis, including minimal cut sets definition and determination of the major basic events which would be solved in the stage of improving the design.

Quantitative Analysis of the Fault Tree

After the major minimal cut sets are determined, the relevant probability can be evaluated by quantitative analysis. The quantitative analysis is normally performed by a mathematical approach [5]. Through surveys to obtain the basic events failure probabilities, as well as the probabilities of the minimal cut sets, and then the probability of the top event failure can be calculated. For a fault tree with every independent minimal cut set, the probability of the top event failure is the sum of all the minimal cut sets failure probabilities. However, for the case of elderly falls, it is tough to measure the basic failure probabilities by actual surveys. Therefore, the literature survey is applied to determine the failure probabilities of the basic events. The evaluation results are represented in the strength of evidence, including strong, moderate, and low. The degree of strong means the basic event is described in multiple studies, and at least two descriptions are prospective. The degree of moderate means the basic event is described in various studies, and only one description is prospective. The degree of low means the basic event is described in few studies, and no one of the descriptions is prospective.

To improve the footwear design more effectively, it is necessary to screen out the basic events which are critical for improvement. Since each basic event performs differently on the top event, as well as the impacts. In this study, mainly considering the basic events in which grades are strong or moderate, which would be analyzed associated with shoe parts. The outcome of this stage would be a ranking of screened basic events.

Design Improvement

Based on the results of quantitative analysis, the improvement of the shoe is mainly focused on the structure, material, as well as accessories. The structure of the shoe is split into seven parts to be modified, including outsole, midsole, insole, stiffener, heel, toe box, and upper. The functions of the shoes would be modified reasonably for the elderly to prevent them from falling. Besides, when they are wearing the shoes, the shoes should conform to their wearing habits. Therefore, the biological, psychological, and emotional changes of the elderly should be considered fully when improving the footwear design. To avoid causing other serious damage of the elderly wearing shoes, the finely balanced decision would be taken.

Following the four phases described above, approaches to reducing elderly fall risk by enhancing the footwear design were proposed, and the detailed results are discussed in the next section.

RESULTS AND DISCUSSION

Fault Tree Analysis

To establish the fault tree of elderly falls, not only the potential causes would be investigated, but also the deeper causes. as well as the interrelationships, should be identified. Thus, methods of literature research and interview were applied.

From literature research, falls among the elderly are prominent for unintentional injury. Elderly falls always occur for complex reasons [9], which has been documented in many studies. Risk factors of elderly falls are regularly classified into intrinsic causes and extrinsic causes [10]. Intrinsic causes include psychological and physiological factors such as loss of concentration, foot deformity, poor posture control, and medical causes [7]. Extrinsic causes refer to most hazards around such as poor lighting, slippery floor, and unsuitable shoes [8]. As the number of factors mounted, the risk of elderly falls would become higher [11].

20 old people aged 60-80 participated in this survey, including 10 males and 10 females. A questionary was designed to collect the relevant information. It was mainly to investigate the potential risks, current health conditions, any measurements taken, whether the fall occurs and consequences. The relevant questions and results statistics were attached, as well as keep their personal information confidential. 55% of participants suffered multiple injurious

falls, and six of them fell more than once. From their recalls, the causes were tripping hazards, loss of concentration, dizziness, low muscle strength, lack of grab bars, limited vision, and poor balance. Besides, 60% of participants have a distinct foot deformity, and they prefer shoes soft and loose.

Based on the results of the literature review and interview, the factors that could lead to elderly falls were cataloged. All causes were deduced from the top event to the basic events to identify the implicit causes. The causes of elderly falls could be divided into categories of external problems and internal problems. The external problems include environmental effects and unsuitable shoes. The internal problems include psychological factors and physiological factors. Those intermediate events would be further deduced level by level until the basic fault events are identified. After all basic events were identified, all events would be connected by the gates. The complete fault tree of elderly falls while walking outdoors is shown in figure 2.

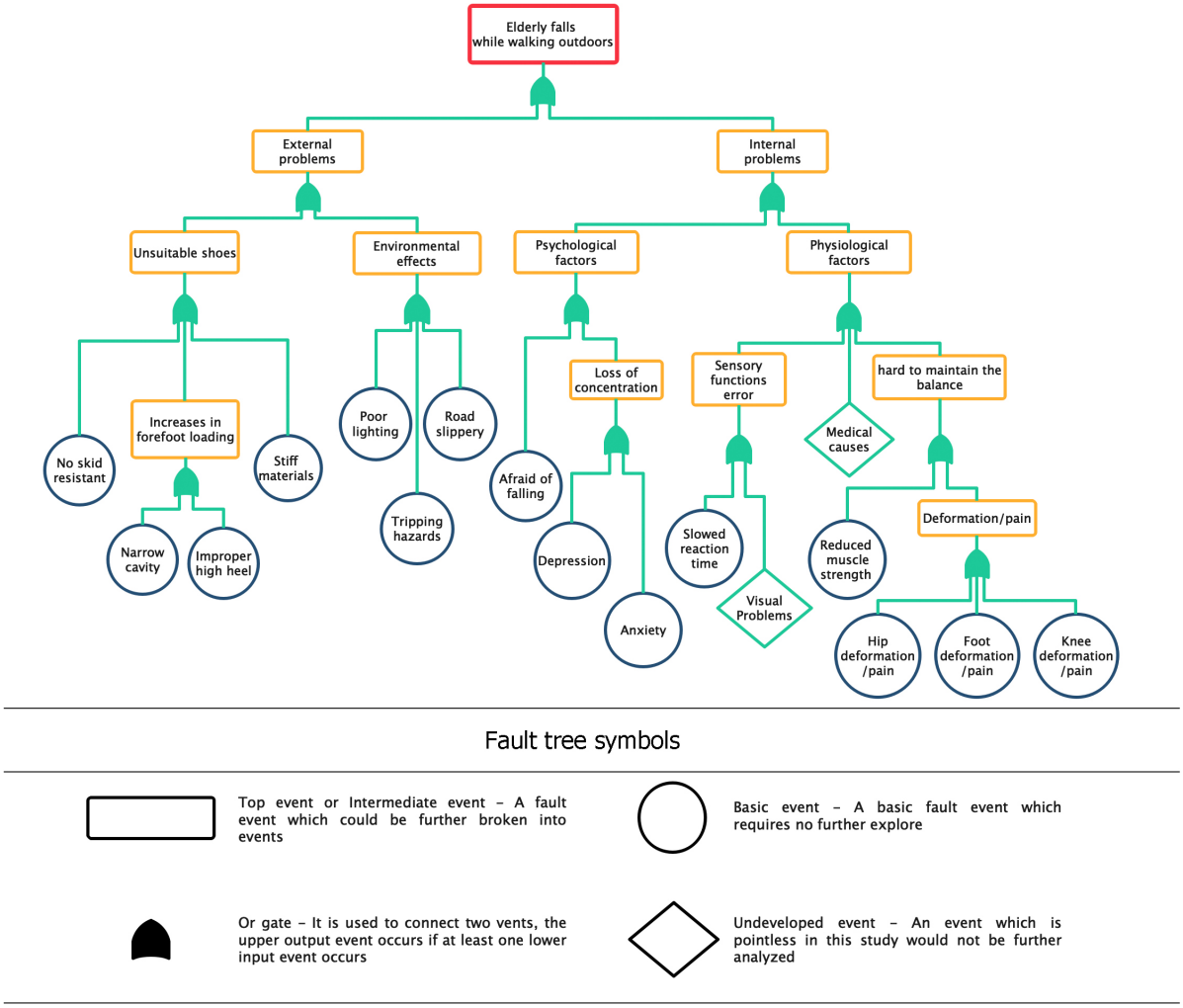

Figure 2. Fault tree of elderly falls while walking outdoors

Qualitative Analysis

Qualitative analysis is principal start from top event to basic events, to sort through the logical relationships between top event and basic events. Thus, the minimal cut sets would be identified which are all basic causes combinations of top event occurs. The fault tree of elderly falls while walking outdoors has 17 minimal cut sets, which are shown in Table 1. Every single basic event from minimal cut sets occurs would lead to elderly falls occur.

Table 1: The minimal cut sets of the fault tree

Num.	Minimal cut sets	Num.	Minimal cut sets
1	No skid resistant	10	Anxiety
2	Stiff materials	11	Slowed reaction time
3	Narrow cavity	12	Visual problems
4	Improper high heel	13	Medical causes
5	Poor lighting	14	Reduced muscle strength
6	Tripping hazards	15	Hip deformation/pain
7	Road slippery	16	Foot deformation/pain
8	Afraid of falling	17	Knee deformation/pain
9	Depression		

At this phase, the qualitative analysis could target the deep causes of elderly falls, and it calls for special concern in the footwear design. For example, the narrow cavity of shoes tends to make the elderly uncomfortable while walking, and less coordination of elderly would be knocked down easily.

However, there is no direct correlation between some unchangeable faults and elderly footwear improvement, especially the environmental situations and some body conditions. Environmental causes include poor lighting, slippery road, and tripping hazards. The effective way to mitigate the risk of falling from environmental causes is to create an elderly-friendly living environment, and a study from Jung shows that a safe living environment could help the elderly to reduce fear and anxiety from falling [12]. As for the causes of using medicines, elderly people tend to take all kinds of medicines to get healthy. The falling risk would be increasing if the prescriptions are not from professionals directly, because some non-adherence drugs would cause dizziness, stiffness, or judgment errors [9]. In addition to the faults associated with feet, the faults associated with other parts of the body would be not analyzed anymore in this study.

Thus, for optimal elderly footwear improvement, the minimal cut sets of environmental factors, medical causes, slowed reaction time, visual problems, hip deformation/pain, and knee deformation/pain would not be discussed anymore in the following analysis.

The basic events which would be modified in the elderly footwear improvement are shown in Table 2.

Table 2: The minimal cut sets which would be solved in the stage of improve the design

Num.	Minimal cut sets	Num.	Minimal cut sets
1	No skid resistant	7	Depression
2	Stiff materials	8	Anxiety
3	Narrow cavity	9	Reduced muscle strength
4	Improper high heel	10	Foot deformation/pain
5	Afraid of falling		

Quantitative Analysis

The main task of quantitative analysis is to obtain the probabilities of the minimal cut sets. Based on the literature review, the probabilities of each minimal cut set would be determined in the strength of evidence and the results are shown in Table 3.

There are six minimal cut sets that are strong predictors of elderly falls, including two factors with shoes, reduced muscle strength, and foot deformation/pain. The risk factor of shoes with non-skid resistance has been described

in numerous studies strongly, and the studies show that anti-slip shoes can reduce fall risks and are suggested for elderly walking outdoors [13-17]. The risk of shoes with a narrow cavity is mainly concerned with foot pain in elderly people. Studies indicated that 26-50% of elderly people wear short or narrow shoes, and shoes are narrower than the foot due to foot deformity and pain [19-22]. Besides, tight shoes in the forefoot could cause gait to become unsteady and walking speed to decline [23]. The risk of shoes with improper high heels is associated with increased forefoot pressure and impaired balance for the elderly [19, 24, 25]. Besides, the experimental results show that high heels led to sway in a 16% increase rate compared to the flats [26]. Reduced muscle strength is associated with the movement of elderly people, the muscle force needs to be generated to control the movement in the balance performance [6]. The review indicated that low extremity weakness is a significant factor of falling [36]. The factor of foot deformation/pain is mainly associated with postural stability and impaired balance [37, 38]. Longer and wider feet of the elderly can help to improve postural stability, deformations of foot arch would affect postural stability, and the hallux valgus deformations would reduce postural stability [39].

Two risk factors were identified as moderate strength of evidence, including shoes with stiff material and depression. Shoes with stiff materials which are unsuitable for the elderly's painful feet and foot deformities have been described in several studies, which also indicated that the elderly would prefer shoes with soft material [13]. Besides, some studies specified that the hardness could enhance balance, and suggested suitable footwear with thin, hard soles for the elderly to wear [18, 19]. For the psychological factors, depression is support by moderate evidence. Depression was evaluated as an impaired cognitive function that is associated with increased risks of falls in multiple studies [31]. A study shows that the falls risk of depressed elderly people is higher than elderly without depression [32]. However, whether the metal impairments related to the psychomotor causes are still uncertain.

Two psychological factors include fear of falling and anxiety were low evidence of causes for falls. Afraid of falling means elderly people lose confidence in their ability to walk or stand [27]. There are several studies indicating that health status is related to the fear of falling, and this is a risk factor of activity restrictions [28, 29]. It is likely that elderly people with impaired gait would have a greater risk of fear of falling, fear of falling would also result in depression for elderly people [30]. However, none of the descriptions prospectively shows that fear of falling would lead to falling. From previous studies, anxiety may impact the risk of falls. Some studies examined the relationship between anxiety and fall, the results are different based on different types of anxiety and sex [33-35]. Thus, more information is required to determine the association between anxiety and falls among the elderly.

Table 3: Strength of evidence for the minimal cut sets

Num.	Minimal cut sets	Strength of evidence
1	No skid resistant	Strong
2	Stiff materials	Moderate
3	Narrow cavity	Strong
4	Improper high heel	Strong
5	Afraid of falling	Weak
6	Depression	Moderate
7	Anxiety	Weak
8	Reduced muscle strength	Strong
9	Foot deformation/pain	Strong

Improve the Footwear Design

Based on the results of quantitative analysis, the minimal cut sets in which the evidence strength are strong or moderate would be mainly considered in the improvement. The risks of elderly falls include shoes with non-skid resistance, shoes with stiff materials, shoes with a narrow cavity, shoes with improper high heels, depression, reduced muscle strength, and foot deformation/pain would be solved in this improvement.

At first, the risk factors of strong prediction were emphasized. For the slip resistance consideration, choosing both material and pattern shape must be careful. The thermal plastic rubber (TPR) outsole performs well in most slippery conditions to keep elderly people away from slip [40]. The pattern shape is responsible to grip the floor, the prominent hackle type would be applied and then repeating on the outsole. For the risk factor of the narrow cavity, which is also associated with the causes of foot deformation/pain. The cavity of shoes should be adjusted to fit the foot deformations from the elderly. The most common foot deformations include hallux valgus foot, foot arch collapse, and toe deformities [13]. The toe cap cavity would be adjusted wider at the metatarsophalangeal joint and toes with material softening. The insole would contain a hard piece at the foot arch to support the arch. Considering the high heel could lead to forefoot loading increased and balance impaired, the flat outsole would be applied. The risk factor of reduced muscle strength is highly associated with elderly falls. There are several studies that tried to solve this issue by textured or vibration insoles [41, 42]. However, the study also indicated that the investigation of the prolonged effects still remains [43]. At this phase, to help the elderly to keep balance better, a flared sole would be applied in the design.

The two moderate risk factors of falls involve shoes with stiff materials and depression. The upper material choice is a laminate with carbon fiber, the carbon fiber could provide spring and strength to shoes. Leather would be applied on the side of the foot, and rubber on the outsole. The study shows that family concerns could help elderly people to relive depression [33]. Based on this consideration and to ensure elderly safety if they fell, the function of auto alarm with sensory of falling, GPS, and RFID would be integrated within shoes. In that way, their children could be noticed by the phone at the first time if they fell.

The model safe footwear for elderly people to prevent falling would have a broad flat slip-resistant outsole, suitable cap cavity with proper material, foot arch support, and auto alarm of falling. Figure 3 shows the key features of the improved footwear design.

Figure 3. Features of the improved footwear design for elderly people

CONCLUSIONS

The results from this study presented that there are at least 17 risk factors for elderly falls. Seven of them were identified as strong or moderate problems and could be mitigated by improving the shoes. The seven risk factors include shoes with non-skid resistance, stiff materials and narrow cavity of shoes, improper high heel, depressed mood, reduced muscle strength, and foot deformation. The design was focused on slip-resistant, wider toe cap, foot arch support, the flared sole and GPS integration. The improved functional shoes could be considered as an appropriate intervention for elderly falls issues.

However, further study is suggested to determine the effectiveness of elderly falls. A large size of sample is required to define the strong evidence of the effect, and a long-term validation is necessary to identify whether the fall rate is reduced by wearing the functional shoes.

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