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Avoiding Fall Related Injuries in Older Adults – An Interdisciplinary Design Approach

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Abstract

Because of the frequency and severe consequences of falls in the elderly, falling is one of the major public health issues. It would be a substantial improvement to reduce the severity and occurrence of post fall injuries. Several technical devices are already used to reduce the risk of falling (e.g. walking aids) or to detect falls (e.g. sensors worn on wrist). However, the underlying biomechanical and kinematical principles predicting falls and their direction remain unknown. Further research and evaluation are therefore necessary in this field. The presented findings will help to close this gap and will be a first step towards an interdisciplinary approach for a personalized design of an airbag system for the prevention of fall-related injuries in the elderly. In a first step, we evaluate possible ways to predict falls and fall directions using kinematic and biomechanical parameters. In a second step we analyse existing products, which aim at detecting falls and avoiding fall-related injuries in regard to compliance and technology acceptance. The research findings of the human movement science and the results of the product-analysis will be transferred into the product development process of fall protection system preventing fall-related injuries in the elderly.
One final result will be a design approach for a variable and modular design of a fall protector.

Keywords: Fall Direction, Fall Prediction, Fall Protection Systems, Universal Design, Variable Design

1 Introduction

In the western world, the demographic change shows itself in a decreased birthrate and an increase of the expectation of life, leading to an estimated proportion of the over 65-year old people of more than thirty percent in 2060 in Germany (Statistisches Bundesamt, 2015). Due to this demographic change, the question of how to stay healthy, mobile and independent into old age, is becoming more and more important not only for the individual, but also for the whole society.
Falls – defined as "unintentionally coming to the ground, or some lower level and other than as a consequence of sustaining a violent blow, loss of consciousness, sudden onset of paralysis as in stroke or an epileptic seizure" – are frequent among the elderly (Kellogg

International Workgroup, 1987). More than 30 percent of people aged 65 and over fall each year and the frequency of falls increases with age (WHO, 2007). Up to thirty percent of the falls result in moderate to severe injuries, usually having a major impact on quality of life and entailing fear of falling and further reduction of mobility (Chan et al., 2007). Moreover, traumas resulting from falls are the second most common cause of death in the elderly (Doulamis et al., 2010). Because of the frequency and severe consequences, falling is one of the leading causes of serious health declines in older adults, making the prevention of falls and fall-related injuries a major public health issue.

The reasons for falls in the elderly have already been well researched and lead from reduced strength to cognitive decline. Further studies show a positive effect of different training programs on the reduction of fall risk (Gillespie et al., 2009). However fall risk does not fall to zero, therefor in recent years, the possibilities of technical devices in the field of fall-prevention and -detection have become more important. Some studies have presented fall-detection devices in order to rapidly alarm medical services in case of a fall (post-impact) (Noury et al., 2007). Other studies have developed devices to detect falls prior to impact using angular correlation of body segments (pre-impact) (Nyan, Tay & Mah, 2008). Nevertheless, there have only been a few studies evaluating the underlying kinematic and biomechanical principles predicting falls and their direction. Moreover, the FARSEEING project, which wants to improve the prediction, identification and detection of falls, recently pointed out that "positive messages about the benefits of falls technologies for promoting healthy active ageing and independence are critical, as is ensuring that the technologies are simple, reliable and effective and tailored to individual need" (Hawley-Hague et al., 2014, p.416).

Fall events and products for protection are observed from the biomechanical and the engineering point of view. The contributions are therefore manifold. In the following it is our main focus to understand falls from a biomechanical view and to derive a design approach that copes with the requirements from the heterogenous target group on one side and with low acceptance on the other side.

2 Prediction of falls – biomechanical and kinematical aspects

A stable gait pattern is one of the most important aspects of falls prevention. Several biomechanical and kinematical aspects have already shown to be important in order to maintain gait stability. For example, active rolling movements of the foot and ankle joint as well as stabilization of the pelvis from heel strike to midstance are necessary to maintain stability and to move forward simultaneously (Perry, 2003). Moreover, the maximum ground reaction forces, the gait line and the step length and step width have proved to be important characteristics of gait stability. Furthermore, a review by Hamacher et al. (2011) has shown that the variability of stride, swing and stance time is an indicator of gait stability and can be used to discriminate between fallers and non-fallers

Michnik and colleagues (2014) point out that "cognition of kinematics of body movement during balance loss, fall and collision with the ground in various circumstances is a basic condition of both expanding our knowledge of these phenomena and optimizing effective prevention of falls and collisions with the ground and vertical obstacles" (Michnik et al., 2014, p. 233). Most studies concerning the fall itself use accelerometers or gyroscopes to discriminate between activities of daily living (ADL) and falls. An overview of the techniques and systems for fall detection was given by Li et al. (2009). Thus, two main classes of fall detection methods exist, those using only acceleration sensors and those using also further sensors to detect body orientation. Li and colleagues (2009) further explain that complex inference techniques are also used sometimes. By using Probabilistic models, i.e. Bayesian network or Hidden Markov Model, activity recognition accuracy can be improved. Yu (2008)

on the other side presented three categories of fall detection systems: wearable devices, i.e. sensors worn on wrist, head, or torso, and ambience devices, i.e. surveillance and other monitoring systems, and also states camera-based systems as third category of fall detection systems.
However, despite of the existing and still ongoing research concerning the fall itself, only a few studies so far have examined its biomechanical and kinematical characteristics. For example, Nyan and colleagues found that the relative angle of body configuration at threshold level for sideways and backward falls was about 40-43° for the sensor at the waist, about 43-52° for the sensor at the sternum and about 54° for the sensor at the underarm (Nyan et al., 2006). In a later study they extended these findings, showing that the angular characteristics of thigh and torso segments highly correlated (corr > 0.99) in falls, while they only showed a low correlation in ADL. All falls could be detected by using the correlation-values and it was possible to generate an alarm 700ms lead-time before the impact (Nyan et al., 2008). Lindemann and colleagues (2005) also proposed different thresholds triggering a fall, namely: the sum-vector of acceleration in the xy-plane being higher than 2 g; the sum-vector of velocity of all spatial components right before the impact being higher than 0.7 m/s and the sum-vector of acceleration of all spatial components being higher than 6g. Wu (2000) compared the horizontal and vertical velocities (measured at various locations of the trunk) during normal activities of daily living and falls. He found that during falls the magnitude of both velocities increased dramatically and that this increase occurred simultaneously, while the velocities during normal activities were in a well-controlled range and usually only affected one velocity at a time. He therefore concluded that the magnitude and timing of the horizontal and vertical velocities could be used to distinguish fall movements from normal activities (Wu, 2000).

3 Direction of falls

> "As most of the falls occur during intentional movements initiated by the person, they happen mainly in the antero-posterior plane, forward or backward: stumbling on an obstacle during walking, backwards slip on wet ground, transfer "Stand-To-Sit"." (Noury et al., 2007, p. 1665).

However, the direction of a fall often remains unknown because people who fell are not able to report what had happened exactly (Chan et al., 2000). Therefore most of the knowledge about fall-directions comes from prospective or real-life studies. For example, Vlaeyen and colleagues (2013) found in a video-based real-life study, that participants mainly fell backwards. Moreover, they suggested an extension of the falls-classification by Noury and colleagues (2007) by distinguishing two separate critical phases. In one phase balance is lost and in another phase balance recovery failed, leading to the actual fall (Vlaeyen et al., 2013, p.1). The results of Weerdesteyn et al. (2012) also point in this direction, showing that a more forward tilted trunk and a further backward positioned leg at the instant of the first stepping-foot contact increased the probability of successful balance recovery after a backward postural perturbation. Ko and colleagues (2007) found in a prospective study, that stride width could be used to discriminate between side-fallers and other-directed fallers with side-fallers exhibiting narrower stride widths compared to other-directed fallers.
The results of these studies already give an insight into some biomechanical and kinematical aspects of fall-directions. However, until now only very few studies have dealt with these aspects and therefore the state of research concerning the underlying biomechanical and kinematical principles of falls is incomplete.
Beside these biomechanical aspects of fall-directions, another interesting aspect is that it influences the rate of hip fractures, which are the most important injury related to falls with

more than 90 percent of all hip fractures being caused by falls (Robinovitch et al., 2000). Moreover, the hip fracture incidence rises with age, which cannot be explained by the frequency of falls or the lower bone mineral density alone. This might indicate that the circumstances of falls may affect the risk of injuries like hip fractures (Schwartz et al., 1998). Smeesters and colleagues (2001) examined the fall direction and pelvis impact location resulting from four disturbances (faint, slip, step down, trip) at three gait speeds (fast normal, slow). They found that "[…] slipping or fainting while walking slowly was more likely to result in an impact on the hip, suggesting a greater risk of hip fracture" (Smeesters et al., 2001, p.309). In a prospective case-control study of 132 ambulatory residents by Greenspan et al. (1998), those who had fallen sideways were also more likely to suffer a hip fracture. Summarising, falling is a complex process with non-predictable consequences regarding direction of fall and severity of injuries. In addition, falling depends on diverse influential factors, such as anterior movement and velocities.

4 Fall protection systems

As fractures – mainly those of the hip – are a major adverse outcome of falls, the prevention of these fall-related injuries is of great interest. Until now, there already exist several hip protectors which are meant to decrease the magnitude of force to the hip during falls as well as the peak pressure and to influence the characteristics of force-distribution in order to minimize the risk of fractures (e.g. Choi et al., 2010).

We distinguish two kinds of systems to directly reduce and avoid fall-related injuries, also known as hip protectors. The first kind of hip protectors is a functional piece of clothing, in the second kind a fall detecting system is included. Some researchers may also define smartphone apps or medical alert devices as injury-reducing-systems. But since these devices can only reduce injuries indirectly by contacting emergency and nursing personnel, we do not include them in our overview.

Illustrated in figure 1 is a simple hip protector. This is usually some kind of underwear, shorts or belt with hard or soft pads sewn into the clothing (figure 1, person shown from the front, belt and pads are shaded, pads with thick line). They are usually worn under the normal clothing. When falling occurs, the pads distribute the impact forces over a larger area and therefore reduce injuries. Lauritzen et al. (1993) examined the effect of a hip protector with polypropylene pads on hip fractures in residents of a nursing home. They found that the hip protector reduced the risk of hip fracture by 53%. Similar compliance results (50,3%) were conducted by Chan et al. (2000). In contrast to Lauritzen et al. (1993) they chose EVA foam as pad material which is softer than that before. However, acceptance of the hip protector is low, only 24% of the residents wore them regularly (Lauritzen et al. 1993). In a similar study reasons given by the residents for not participating in the study and thus for non-acceptance of the hip protector were discomfort (37%), poor fit (26%), physical difficulties (13%), illness (7%), and forgetfulness (4%) (Villar et al., 1998).

The second kind is a device with inflatable cushions similar to an airbag-system (figure 2, person shown from behind, inflatable cushions with thick line). Only when falling is detected, the cushions inflate with a gas within 60 milliseconds (Active Protective), the cushions are stowed in the belt. The belt therefore has to be worn on top of normal clrothing. To detect falling, a falling predicion system, such as explained above, is also necessary.

Inflatable systems are shown in several patents (Davidson, 2004; Lockhart, 2005; Buckman, 2009). Davidson (2004) described a system to be worn on the waist with the inflatable parts mainly on the back to reduce injuries from falling backwards and also to cause the body to assume a sitting position through inflating. Lockhart (2005) describes the inflatable airbag protection device with focus on the fall prediction system. Buckman (2009) describes both, inflating system and fall prediction system, in detail. First products are expected to be ready for market in this or the next year (e.g. Hip Hope Technologies). Unfortunately, no research about compliance and acceptance of these systems exist. Regarding compliance, we believe that risk of hip fracture is lower by using inflatable hip protectors than by using simple hip protectors, since air bags are better shock absorber than foam or plastic.

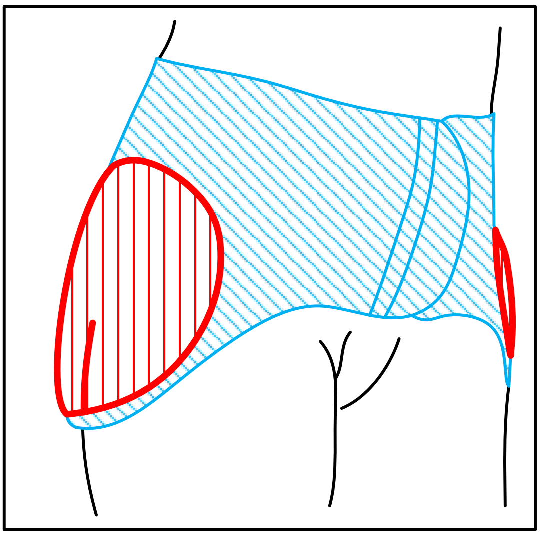

Figure 1: Simple hip protector with two pads sewn into a belt

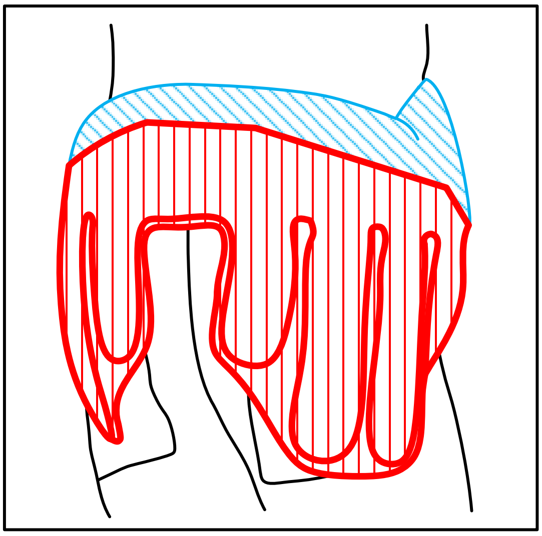

Figure 2: Inflatable hip protector (according to Active Protective)

However, these airbag concepts have a high risk of low acceptance in the target group. First, they will be probably too expensive, if health insurance does not pay for them and/ or they cannot be reused after inflation. Second, they need a tight fit but also are very thick, when chushions are packed inside the belt. Because of that, users probably will not want to wear the system in bed and therefore still have a risk of falling out of bed. Third, the design of the protectors could be stigmatising for users: they are only used by elderly people with reduced strength and stability as well as are visible for others.

Even though effectiveness in reducing the risk of hip fracture in the event of a fall of hip protectors has been proved, technology acceptance is low. Davis (1986) described technology acceptance using two main prerequisites: ease of use and perceived usefulness of products. His “Technology Acceptance Modell” and most of the subsequent work is evaluated using information and communications technology (ICT). Interest of older adults in new technical developments in this field is similar to that of younger adults, but in contrast, older adults are much more critical regarding usability issues and cost (Mallenius et al., 2007). However, after purchase full adoption of the product will not occur, if ease of learning and use is not given (Renaud and van Biljon, 2008).

Regarding medical or support devices, e.g. hip protectors, we see a different attitude of users. These products are more likely to be rejected by users. For example, elderly usually avoid walking aids as long as possible, even though walking aids, especially newer designs, ensure a better stability and posture. Social psychology theories suggest that customers refuse to adopt age or disability related products, because this wouldn´t fit to the actual or the ideal self-image of not yet belonging to the group of the “old” or the “disabled” (e.g. Moschis, Mathur, 2006). According to Hawley-Hague et al. (2014), emphasising the benefits might increase acceptance of medical devices. Therefore, besides usefulness and ease of use, also extrinsic factors, such as pricing and relatives encouraging the usage, as well as intrinsic factors, such as demographic factors and status, needs also to be taken into account when analysing acceptance (e.g. Mallenius et al. 2007, Renaud and van Biljon 2008).

For our development we conclude, that product acceptance is presumable lower, (1) if the product is associated with a specialised design for elderly or persons with sickness or disability (due to the negative impression of being old and or sick); (2) if cost of the product outweigh the benefits; (3) if the product is not easy or not comfortable to use.

5 Design approach for an fall protection system

Regarding design methodologies, integration of universal design (UD) principle into product development process (e.g. described by Kett and Wartzack (2015)) may be a potential solution for acceptance dilemma. Here, products and environments are designed “to be usable by all people, to the greatest extent possible, without the need for adaptation or specialized design” (Connell et al., 1997, p.107). This is important, because our target group cannot be defined only be age, but also by physical impairment leading to a higher risk of falling. These are just as diverse as falling incidents themselves; and so are also life situations of users in the target group. UD products are suitable for larger group of useres, not only for elderly people (acceptance statement 1), and usabilty, i.e. ease of use, can be increased (acceptance statement 3) through UD principles.

However, due to non-forseeable psychological and pathological aging processes, older adults are a highly heterogeneous target group with diverse and variable requirements and wishes. As explained above, fall events are diverse and non-predictable. Kinematic thresholds for fall detection depend on body posture and anterior movement. Risk for fall injury probably depends on fall direction. Preconditions to fall and movements leading to falling are therefore manifold. Lockhart (2005) proposed a learning mode to sense and calibrate individual thresholds. These can also change over time and have to be taken into account when designing fall protection systems with inflatable cushions.

Moreover, cushions or pads for injury protection should be designed according to individual body shape and body weight. The whole system should be adaptable or usable for different applications, e.g for day and night. Design should be unobstrive and hidden under clothing, without decreasing comfort or aesthetic demands of users. In regard to acceptance, inflatable systems has to be reusable after inflation to make the system affordable (acceptance statement 2). Looking at these diverse requirements, it is obvious that one design for every single individual, does not fit at all. Therefore using UD strategies alone probably will not lead to solutions with high compliance and acceptance.

A design approach also including methods to ensure variable product design is therefore proposed. Here, we see different approaches, such as Design for Flexibility /Flexibility for Future Evolution, which refers to the ability to redesign a product quickly and inexpensively to meet changing requirements (e.g. Tilstra et al. (2013)), or Design for Adaptability, whereby “adaptability is the capability of a system of being adapted for changing circumstances by external intervention” (Greisel et al. 2013, p.3). These approaches build on a modular product structure, provided by modularization approaches such as Krause et al. (2014). Our goal is to enable a product/ product family to change or adapt functionalities during the use phase, in order to react to the changing requirements of users and use case, without increasing cost and expenses of product development. At the same time, acceptance could be increased by including UD principles.

The design approach (illustrated in figure 3) can be described as follows: Using the product development process of Pahl and colleagues (2007) and the method for Integrated Development of Modular Product Families (Krause et al., 2014) as basis for our approach, a modular design concept for a new fall protector can be developed. UD principles – 7 in total - are included during Task Clarification to derive further requirements and also at the end of

Conceptual Design Phase to evaluate the developed concepts. Resulting requirements are, for example (Connell et al., 1997):

- Principle 1: "Equitable Use" indicates that the fall protector design should be transferred to other applications, where people fall frequently, e.g. skiing. Stigmatising and bad image could be avoided, if also young and healthy people would use this kind of system for sporting activities.
- Principle 3: "Simple and Intuitive Use" emphasises that in spite of the modular and adaptable design, unnecessary complexity should be removed from the product, i.e. interfaces for frequently done adaptations, such as putting on and removing protector, should be performed easily, while interfaces for rarely done adaptation, such as adjusting of body weight and size, must not be able to activate/ detach by accident.

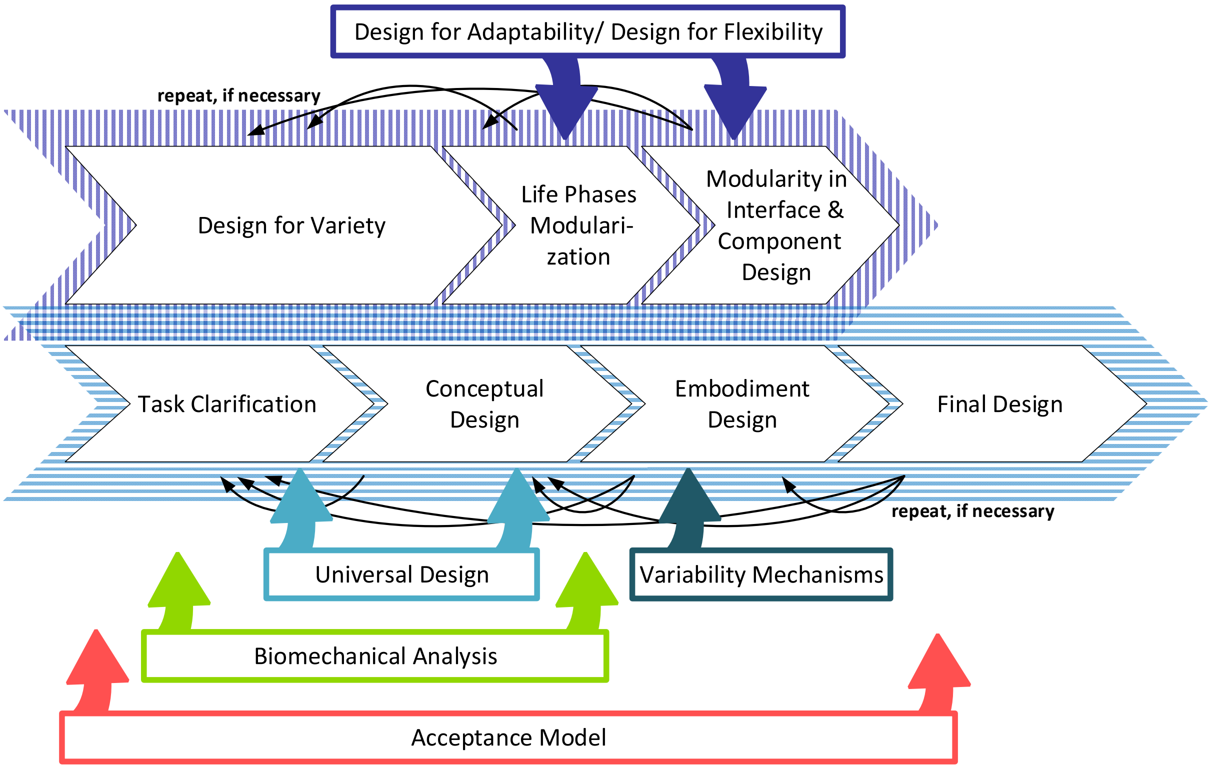

Figure 3: Design approach for a fall protection system

Approaches for Adaptability and Flexibility can be implemented in the integrated modularization approach in regard to the actual design tool described. For example, Greisel et al. (2013) defined adaptability drivers. These can be used in the modular design of the product family and enable modules to be more adaptable and flexible when product is in use.
Several mechanisms can be also used to enable variability in product design:

- Configurability or Upgradeability: Modules can be upgraded, changed or reconfigured during use phase to enable rarely done adaptations.
- Oversizing: Modules should be oversized to cover changing boundary conditions, which are not completely foreseeable (e.g. changing body weight is no problem within certain limits, if inflatable cushions are oversized).
- Adjustment: Sizes and settings can be changed easily to facilitate frequently done adaptations.

As shown above, for our approach we need an interdisciplinary view. To prove the acceptance statements, interviews or other user integration methods needs to be included at the beginning of the design process and at the end, when prototypes exist. Likewise, biomechanical and kinematical analysis is useful to state requirements for physical design. At a later design phase further examinations will help us to decide on a concept as soon as different concepts for fall detection exist.

6 Discussion

A design approach for a fall protection system was derived after a literature study on fall prediction, fall direction and existing hip protectors has been done. Here, we see need for further research on falling directions. Further, compliance and acceptance of these products has been examined. Main conclusions are that acceptance also depends on product type, i.e. ICT or medical devices, due to associated image and also other intrinsic and extrinsic factors. However, a detailed study examining these hypotheses is required. This study could also show that other reasons, such as forgetfulness, are a major problem for acceptance, i.e. adoption after purchase.

The modular and variable concept for a fall protector may improve fit to individual users with diverse wishes as well as for different falling events and at the same time may improve acceptance due to further marketing channels. Since the proposed approach is only a first step, further design and research efforts as well as an evaluation of the overall findings are still necessary. However, when designing actual concepts and embodiments for the fall protector, the design must not violate existing patents.

Apart from fall protectors, we strongly belief, that our approach is also practicable for other systems and applications. Depending on future findings and system, other non-technical research fields, such as management or social sciences, may be included in the interdisciplinary approach.

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