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Stair Climbing Aid Devices as Parts of Sustainable Healthcare

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An important aspect of a sustainable society is the care of elderly people. For a sustainable society, it is necessary to develop cost-effective, culture-appropriate, and sustainable eldercare services, which should guarantee both safety and quality. It is also important to prolong the time in which elderly people can live independently to contribute to sustainable healthcare. For elderly people, a daily activity, climbing stairs, might be difficult. This paper presents an overview of stair-climbing aid devices. The paper introduces the sustainable healthcare of elderly people. Then, different stair-climbing aid devices are explained and analyzed, ranging from passive ones to high-tech stair-climbing exoskeletons. A prototype of a new solution, which is an Intelligent Crutch, is presented. After elaborating on the design criteria, the detailed conceptual design and the working principle of the device are presented. The presented concept fills a gap between expensive and complicated stair climbing aid devices and simple and cheaper solutions. It is cheaper and simpler than the active, complicated stair-climbing devices but performs almost the same function. The device helps elderly and disabled people to climb stairs alone, thus improving the quality of life of the target group. The study concludes with further development tasks in order to help elderly people and contribute to a sustainable society.

1. Introduction

The population in the European Union (EU) is becoming older, and this trend is expected to continue. The percentage of people above 65 years old was 20.3 % in 2019 of the total population, and it is projected that it will double over 50 years (Eurostat, 2020). People aged 55 years or more took 33.6 % of the EU-27 (member states of the EU at 01.01.2007) population. Very old people (more than 85 y old) took 2.8 % of the EU-27 population in 2019. It is also projected that the number of people aged 75-84 will rise by 60.5 % and the number of people aged 65-74 will increase by 17.6 % (Eurostat, 2019). The increase in elderly people has an impact on economic growth, carbon dioxide emissions, energy use, and sustainable development (Pais-Magalhaes et al., 2022). In 2019, 39.7 % of old people were living in intermediate regions, 38.2 % in predominantly urban regions, and 22.1 % in predominantly rural regions. In 2018, 58 % of men aged 65 years or more shared their household with their partner but with no other person. Only 39 % of old women shared their household with their partner, which means there are more old women living alone (40.2 %). For alone living old men, this share was 21.8 %. Most older people live in private households, but some of them move to institutional households (Eurostat, 2020).

Sustainable development has many branches, for example, developing renewable fuels (Ganev et al., 2022) and sustainable energy management (Rosso-Cerón et al., 2022). Sustainable healthcare also contributes to sustainable development (Li et al., 2021). The sustainable development goals of the United Nations include that all people of all ages enjoy prosperity and healthy lives (UN, 2015). For a sustainable society, it is necessary to develop cost-effective, culture-appropriate, and sustainable eldercare services. The sustainability of eldercare services should guarantee both safety and quality. Sustainable eldercare can be private or public or a combination of them with ready-to-use technology to accommodate the needs of older adults (Marinelli et al., 2022). It is also important to prolong the time in which elderly people can live independently to contribute to sustainable healthcare.

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It is a known tendency for more and more people to move into cities. It is projected that more than 2/3 of the world will live in urban areas by 2050, which means close to 7 billion people (Our World in Data, 2018). As the place in cities is limited, urbanization leads to the establishment of multi-storey buildings (Giyasov and Giyasova, 2018). Up to now, construction of elevators in four-storey and lower buildings wasn't compulsory in most countries. An outcome of this process is that a non-negligible part of elderly persons lives in multi-storey buildings without elevators. Adding to this the fact that getting older, more and more medical problems occur, for example, weak muscle mass and strength, heart weakness, overweight, cognitive decline, and so on. As a consequence of the above, many people have serious difficulties leaving their homes because stair climbing is an unsolvable task for them. Going shopping, taking down garbage, walking in the fresh air, and meeting friends is part of the daily routine and healthy life. A primary interest of society is to sustain the mobility of older and disabled persons. Enabling people to live in their own homes as long as possible is a humane and economical achievement. This mission can have a role in the development of a device that facilitates stair climbing of people. This paper presents a prototype of a new solution.

2. Theory – Stair climbing aid devices

In this section, different stair-climbing aid devices are reviewed. Depending on the level of disability, assist devices can be divided into passive or active ones. Using passive aids like walking sticks, walkers, or crutches, people must rely on their own muscles. The net energy consumption is the same without or with these devices. The difference is, for example, that foot muscle force can be replaced or completed by hand muscle force. Another possibility is to reduce the range of motion and power of muscle activity by half-step auxiliary stairs like EZ-Step (2023).

Active devices operate with an additional energy source. There are various stair-climbing mechanisms, wheelchairs, and different kinds of exoskeletons. Many dozens of stair-climbing wheelchair constructions are known in the literature. There are wheel-, wheel-cluster-, track-based, articulated, and hybrid mechanisms. Pappalettera et al. (2023) reviewed them in detail. These devices are expensive, spread, and need an assistant person to operate them safely. There are also academic developments (Lawn, 2002), but they are more and more complicated. Exoskeletons are attached to the body and make up the muscle force of the user with different kinds of actuators. They gain particularly military application, but also their rehabilitative and industrial usage is significant. Lovrenovic and Doumit (2019) presented a detailed review of them. Most of them are robust and too expensive for seniors, and attaching them alone to the user's body is almost impossible. The only exception is HONDA's walking aid device (Ikeuchi et al., 2009), which goes through all requirements except for its high price.

Looking through the known passive and active solutions, one can recognize that there is a gap to be filled between passive and active aid devices for those who are even mentally intact and motile but have weak muscle mass and strength (sarcopenia) or are overweight. Drawing the design criteria, the goal of the research is to propose an affordable device that is capable of helping stair climbing of the mentioned group.

3. Design

3.1. Design criteria

As the target segment of users is not conventional, it is necessary to determine the requirements for novel equipment. The following aspects are to be considered:

- **Mobility.** The user can use the device without the help of an assistant, even with stairs of different sizes, either in apartments or in staircases.
- **Stability.** Special attention must be paid to the relationship between the person's center of gravity and the line of action of the force acting on the body.
- **Easy and quick usage.** The user can put the equipment into practice quickly and easily. No straps and buckles allowed. The connection of the device with the body cannot be hindered by wearing various pieces of clothing (skirts, trousers, winter coats, etc.).
- **Easy portability.** Since it is a mobile device, it should be light in weight and size to be easily transported. When not in use, it can be stored in the trunk of a car or on the ground floor of a staircase.
- **Low cost.** Elderly and sick people usually live in worse financial conditions, so access to the device must be ensured for them at an affordable price.
- **Easy handling.** The structure is usually used alone by elderly people, for whom simple and safe handling is essential.
- **Operating time.** With continuous operation, the structure must be able to climb to a height of 4 floors (at least 6 min. continuous operating time).

- **Kinetics.** The user's muscle strength must be supported by a vertical force of at least 250 N, with a lifting speed of 4-8 cm/s. The structure must be able to lift itself while climbing stairs. The user should not have to lift it.

3.2. Conceptual design of an intelligent crutch

Before designing a mobility aid for stair climbing, some functions of this device are to be discussed.

a) Locus of interaction between body and device.

It is a fundamental task to find the place where the force/torque should act on the user's body while climbing a stair. Opportunities to consider are knees, hips (torque), buttocks, and armpits (force). Helping the motion with torque is not ideal in our case, as the torque must be applied between two connected body parts (leg-thigh, thigh-trunk). Accordingly, the device would have to be attached to each of the two body parts with means capable of transmitting torque (straps, velcros, buckles), which would not allow simple and quick use (Lee, 2017). With a saddle-like structure at the buttocks, the supporting force can be easily transferred to the body (similar to a bicycle). Its advantage is that the force acts in the mid-plane of the body, so it does not tilt to the side. Moreover, it can also be solved that the line of action of the force should pass through the center of gravity (COG) of the body. Applying force in the armpit is also a frequently used solution (see crutch). Using the device on one side of the body significantly affects the natural fashion of walking. It has a side-tilting effect. In addition, mechanical stress on the nerves and blood vessels in the armpit is not medically recommended either. At the same time, using a device acting in the armpit is the simplest solution into use.

b) Ensuring stability

Healthy and young people instinctively lean forward and bring their center of gravity over their front leg while their back leg pushes off the ground and creates momentum that swings the body past its dead center. On the other hand, the members of the target group do not move quickly due to their age or illness, the inertial forces resulting from acceleration and deceleration are negligible, and their climbing stairs can be considered a static process. Since the person's ability to balance can only be partially counted on, special care must be taken to ensure that the line of action of the supporting force preferably passes through the body's center of gravity and points forward.

c) Energy storage

The device must create mechanical movement when supporting stair climbing. The energy to be stored is 3750 J in the case of a 15 m level difference and a 250 N auxiliary force. Assuming that the energy conversion efficiency is 50 % and at least five times ascent is to be ensured, the energy to be stored is E = 37,500 J. In our case, it is not possible to store so much energy mechanically with a spring or a moving mass. This amount of energy could easily be stored in a paintball bottle with compressed air, but filling the bottle to a pressure of 100-300 bar is not feasible at home. In the case of electric energy storage, the charging requirement of a 12 V battery is only E/U=3125 As=0.87 Ah. Besides, according to Russo et al. (2018), rechargeable batteries are the most feasible and efficient solution for energy storage applications. Batteries are also sustainable in a way that their recycling strategy is continuously developing (Latini et al., 2022).

d) Continuity/discontinuity of operation

Modern medical devices (prostheses) obtain information about the user's intention by processing the bioelectrical signals of the muscles. However, ensuring proper contact with the surface of the skin cannot be safely guaranteed in the case of a device intended for laymen. Therefore, the simpler push-button solution can be recommended to solve the step-by-step start and stop. A continuously operating tracked solution can also be considered due to the stable interlocking effect among teeth and the step’s sharp corner. However, this bulky solution is not advisable due to its difficult movement in stairwells.

4. Results and discussion

Considering all aspects, an intelligent crutch (IC) was designed. In the literature, only one attempt is known, where an automated clutch mechanism is presented that assists in level walking of paralyzed people (Higuchi, 2010). The main parts of the Intelligent Crutch can be seen in Figure 1. The discontinuous lifting movement is performed by a self-locking electric cylinder (EC). A lot of self-locking EC can be purchased in the market, but their duty cycle must be taken into account in order to guarantee a sufficiently long operating time. The maximum stroke of the applied EC is 200 mm, which is sufficient for average stairways. The maximum thrust of the chosen EC is 250 N. An important part of the device is the auxiliary leg, which can rotate around a hinge H. It serves as a switching and a load-bearing element, too. First, the spring begins to turn above the next stair when lifting corresponds to the current height of the next stair. At this moment, it opens SW2. Second, going further and reaching its end position, it closes the end switch SW1, stopping the lifting process and, at the same time, drawing back the rod of the actuator at a higher speed.

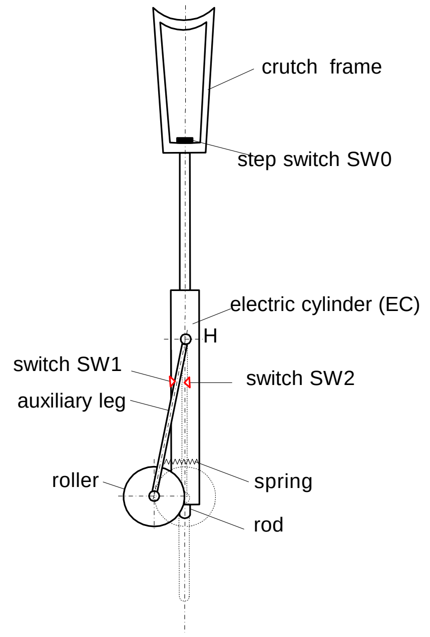

Figure 1: The structure of the intelligent crutch

Third, it serves also as a support surface, bearing the load during pushing forward the device. The climbing movement is controlled with a push button (SW0) and limit switches (SW1, SW2). Each new step is launched by pushing the step switch SW0. Energy storage is provided by a lithium-polymer battery.

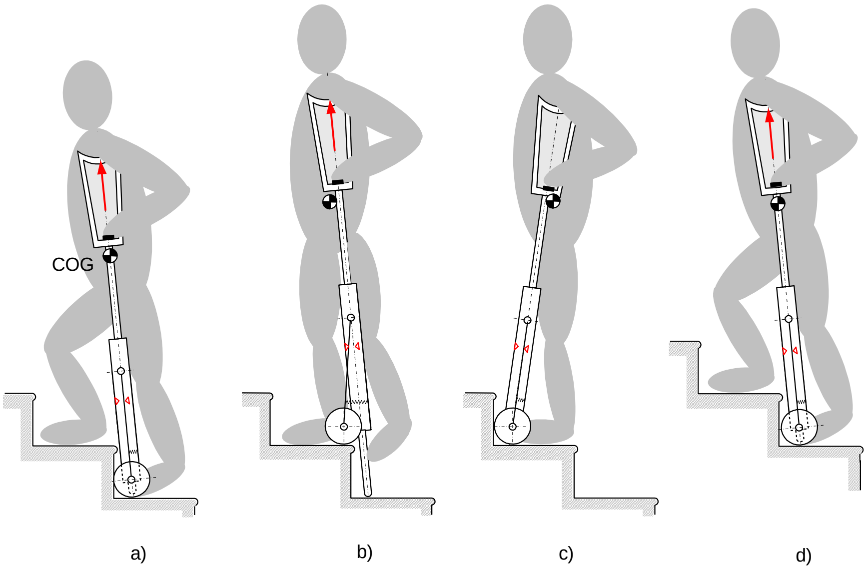

Figure 2: The operation phases of the intelligent crutch during ascending

The stair climbing process takes place as follows: before climbing upstairs, the device rests on the bottom stair, completely pressing the roller against the front of the stairs. The actuator (EC) is fully retracted. The spring is compressed, and switch SW2 is closed. The device is waiting to start (Figure 2a). The user puts one of his legs onto the next stair. By pressing and holding the switch SW0, the actuator starts to increase its length, pushing the person up at approximately constant speed. As soon as one stair step is raised, the spring turns the auxiliary leg, and SW2 opens. The auxiliary leg goes further until its end position, and the switch SW1 closes, which stops lifting and starts to reduce the length of the actuator at the same time. The device rests on the roller while the rod is moving back at higher speed (Figure 2b). When the rod draws back its end position, the user releases the push button SW0 and pushes the structure forward until it hits the front of the next stair step. At that time,

SW1 opens, and SW2 closes (Figure 2c). The user puts his leg onto the next stair, presses the push button SW0 again, and the process of climbing starts again (Figure 2d).
When moving downstairs, the intelligent crutch does not work actively, similar to the walking stick, because the user does not need additional energy. In this case, the rod of the EC is retracted, and the device can roll down to the lower step on its wheel. The user leans on the crutch by his arm (Figure 3).

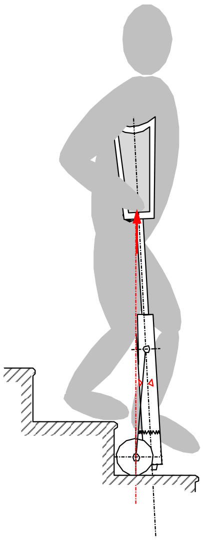

Figure 3: The operation of the intelligent crutch during descending

The control logic (Figure 4) of the intelligent crutch is quite simple. The motor may stop, or it can retract or extend the rod. The direction of the rod movement is determined by SW1 and SW2 switches. Because of safety reasons, the user must not only press the SW0 push button shortly, but it needs to be held during the movement in either direction. During use, it may happen that the auxiliary leg is in a position where none of the SW1 and SW2 switches close. In this situation, the movement continues in the same direction.

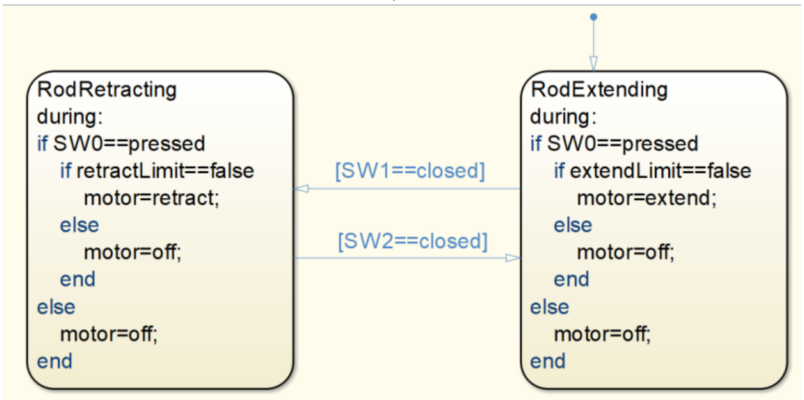

Figure 4: Matlab stateflow chart of the control logic

The solution presented in this paper combines the additional functions provided by active devices. As a result, only a simple control system and only one actuator are necessary. Consequently, this solution is significantly simpler and cheaper (around 600-700 euros) than its competitors while performing almost the same function. The disadvantage of the device is that its use requires a certain attention if the user has to coordinate the forward movement and the press of the start button. The solution allows the target group to climb the stairs without assistance, thus improving their quality of life and therefore contributing to sustainable eldercare.

5. Conclusions

In this article, attention was paid to the importance of sustainable eldercare. One of the possibilities is to create an Intelligent Crutch, which helps seniors and handicapped persons to climb stairs alone, ensuring they leave their homes without the assistance of a guide, improving their quality of life. After elaborating on the requirements, the proposed equipment formed as a result of a detailed conceptual design. The proposed equipment is a mobile, semi-active one that fills the gap between simple passive and complicated active solutions. It makes up for the weak muscle force of its user. The initial variant of the Intelligent Crutch lifts the user at his armpit with an approximately constant speed of 6 cm/s with a maximum 250 N force. Tests of the structure are underway in order to improve its applicability. In the future, it is intended to accomplish the device by trying out several solutions. For example, instead of constant lifting speed, the assist force is to be controlled either by applying a pressure-sensitive switch instead of the push button of SW0 or by measuring the force between the shoe and the stairs. Another issue is to place the equipment between the legs and apply a saddle instead of a crutch. The authors hope that this equipment will ease the lives of many people.

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