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Development of a Stair Climbing Mechanism for a Novel Mechatronic Transport Aid: Preliminary Results

Abstract: Emergency medical service (EMS) is an essential part of health care with the main task to transport and monitor patients. However, this duty often becomes a challenge due to obstacles - especially stairs - on the way. Associated lifting and carrying of patients regularly imposes high loads in unergonomic working postures on paramedics, leading to the highest work induced injury rates among all industries also due to a deficient usability of existing transport aids. Therefore our goal is the development of a stair climbing mechanism for a novel mechatronic transport aid characterized by high mobility and a small footprint, whereby particular attention has to be paid to application specific requirements. This paper presents the general approach accompanied by results of a functional model from an initial concept study. Acceleration and jerk measurements showed promising results, while most predefined velocities on the model test parkour rise could be reached.

Keywords: Stair climbing mechanism, Transport aid, Patient transport, Emergency medical service, EMS

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1 Introduction

12 million deployments are carried out by 63,000 employees of emergency medical services (EMS) in Germany annually with rising tendency [1], [2] . Given that during one third of these deployments private homes are involved [3] which are rarely constructed barrier-free, transportation of patients becomes a challenge. The associated frequent lifting and carrying of patients in harmful postures strains the upper and lower back [4], [5], leading to the highest work induced injury rates [6], [7] and early retirement rates compared to any other industry [8], [9]. In addition with the rising trend of women working in EMS [10], which are more likely to suffer injuries compared to men [11], [12], the issue becomes even more severe.

Different passive or active support systems are aiming at a reduction of related workloads [13], [14]. Passive systems according to the DIN EN 1865 are main stretcher, rescue sling, scoop stretcher, vacuum mattress, spine board and hinged or not hinged carrying chairs. However, environmental conditions such as small staircases limit the usability of these devices and frequently lead to unergonomic working postures [15]. Active systems support paramedics with an additional energy supply to overcome obstacles like stairs for instance and currently find their way into EMS. Simple mechanisms for raising and lowering of the main stretcher have already proofed effective for prevention of injuries [16], [17]. However, more complex stair climbing mechanisms are available but rarely used. This could be due to disadvantages such as the inability to overcome spiral staircases, large dimensions of the device's footprint [18]–[21] or limited mobility.

Main objective of the SEBARES Project is the development of a novel mechatronic transport aid to assist paramedics during demanding transportation tasks while maintaining high mobility and a small footprint. Therefore a suitable stairclimbing mechanism has to be developed and tested specific for use in EMS.

2 Material and Methods

Based on a systematic literature review and analysis of related user requirements a development process following recommendations made by the VDI 2221 is executed. 79 stair climbing mechanisms have been found in the literature and 13 novel stair climbing concepts have been developed. Following, an evaluation of concepts by criteria defined based on our initial requirement analysis is made. The criteria covered include:

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- Safe climbing of straight staircases
- Small operator loads within ergonomic limit of 10kg [22] and physiological postures
- Compact external dimensions to allow climbing of stairs with reference to DIN 18065: 800 mm, 230 mm, 200mm (Width, depth, height)
- Suitability for spiral staircases
- Additional loads of up to 120 kg possible to ensure transport of 98.9% of the German population [23]
- Sufficient velocity comparable to slow walking speed of 1 step/s possible
- Safe ride feeling of patient (rigid structures and little vibrations, accelerations, jerk and noise)

Subsequently, the weighted points score suggested by [24] is used to select initial design concepts. During the initial analysis similarities and obvious contradictions to essential requirements have been identified resulting in 17 concepts, which underwent the weighted points score evaluation. Weights of the criteria were determined by using a preference matrix. Rank, criteria, category and weight are listed in Table 1.

Table 1: Rank, criteria, category and weight for suitability evaluation of concepts

Rank	Criterion	Category	Weight
1	Good climbing capability for straight staircases	Reliability	14.5 %
2	Versatility		14.1 %
3	Good climbing capability for spiral staircases		11.4 %
3	Tilt stability	Safety	11.4 %
5	Low time loss	Comfort	10.9 %
5	Small operator load		10.9 %
7	High patients sense of security		10 %
8	Robustness	Safety	8.6 %
9	Simplicity	Practicability	4.1 %
10	Energy efficiency		2.3 %
11	Compatibility of mechanisms for stairs and flat movement		1.8 %

Finally, scaled down (1:4) functional models of the highest rated concepts are realised and evaluated according their use for a novel mechatronic transport aid. Therefore mechanisms are subjected to staircases with a small (20.5°) and a steep (45°) rise derived from DIN 18065, while climbing speeds are varied between 0.5 steps/s, 1 step/s and 2 steps/s. During the experiments accelerations are measured and scaled according to a reference measurement taken with a carrying chair using the Phyphox App for iOS and Android (RWTH Aachen, Germany).

3 Results

Three concepts were chosen for verification using scaled functional models of which the highest ranked is presented and evaluated in the following.

3.1 Functional Model

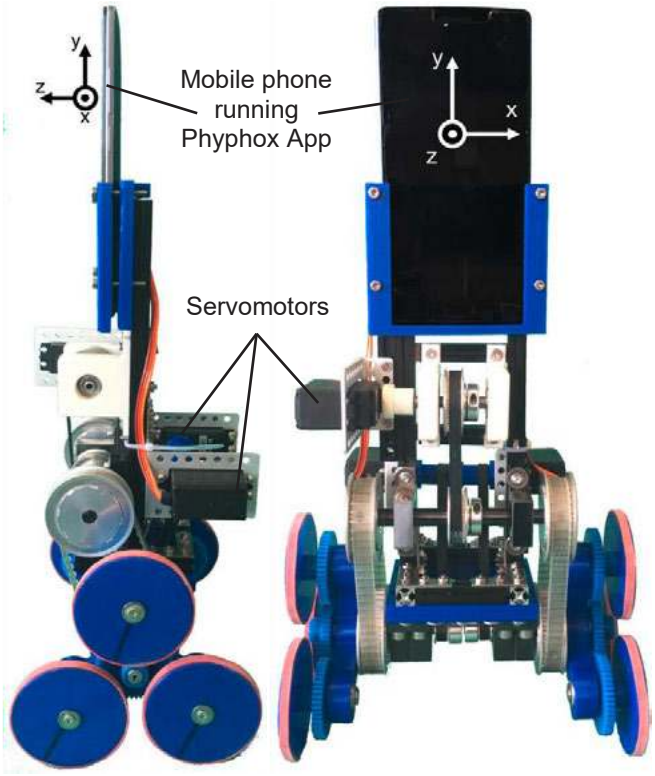

Figure 2: Best rated concept based on Mario Super RD 158 TB (Mario s.n.c., Casalserugo, 35020 Padua, Italy) and the Erect Wheel-Legged Stair Climbing Robot [19]

The downscaled functional model of a stair climbing mechanism for a novel mechatronic transport aid is based on a combination of the Mario Super RD 158 TB (Mario s.n.c., Casalserugo, 35020 Padua, Italy) and the Erect Wheel-Legged Stair Climbing Robot [19]. The model consists of three servomotors from FEETECH (ShenZhen, China) which drive three equally spaced wheels on either side of the functional model and are controlled using an Arduino Nano Board. Thereby the planetary gears are designed to synchronously rotate the planet carriers while enabling

independent speed control of the wheels on either side, to be able to overcome spiral staircases. The final set-up is shown in Figure 1.

3.2 Preliminary Study

5 measurements were taken for each combination of speed and rise for upward stair climbing in a downscaled model test parkour and classified according to a reference measurement taken with a carrying chair. Three classes were defined. First, accelerations or jerk smaller than during carrying (Class I), second, accelerations or jerk smaller than putting down a carrying chair (Class II) and accelerations or jerk higher than putting down a carrying chair (Class III).

Table 2: Classified relative frequency of acceleration and jerk in y and z direction

Rise	Velocity	Class	Acceleration		Jerk	
			y	z	y	z
20.5°	0.5 steps/s	I	99%	88%	98%	94%
		II	1%	12%	2%	6%
		III	0%	1%	0%	0%
20.5°	1 step/s	I	95%	74%	95%	87%
		II	3%	23%	4%	12%
		III	1%	2%	1%	0%
20.5°	1.34 steps/s	I	91%	65%	90%	79%
		II	6%	31%	8%	20%
		III	3%	5%	2%	2%
45°	0.5 steps/s	I	99%	91%	99%	97%
		II	1%	9%	0%	3%
		III	0%	0%	0%	0%
45°	1 step/s	I	96%	74%	96%	82%
		II	3%	25%	3%	17%
		III	1%	1%	0%	0%
45°	1.25 steps/s	I	94%	65%	94%	74%
		II	4%	34%	5%	26%
		III	2%	1%	0%	0%

However, due to limitations of the motors used a maximum speed of 2 stairs/s was not reached such that results of highest speed are 1.34 stairs/s (20.5° rise) and 1.25 stairs/s (45° rise). For comparison, measured accelerations of the functional model were scaled up before classification. The classified measurements of acceleration and jerk in the y and z direction are shown in Table 2.

4 Discussion

The concept of a stair climbing mechanism for a novel mechatronic transport aid was presented in this paper. The development is based on a literature analysis regarding stair climbing mechanisms of several application areas as well as newly developed design approaches. Evaluation of the concepts for the specific area of application resulted in a total of three potential solutions. For further evaluation a downscaled functional model of an initial prototype has been presented.

General feasibility of the concept could be shown as the mechanism met basic requirements in lab settings. However, the predefined speed of 2 steps/s was not reached due to limitations of the utilized motors. Therefore more performant motors will be implemented in the final functional prototype.

Acceleration measurements were classified according to an upstairs and downstairs reference measurement with a carrying chair and showed promising results. The recorded data suggests that with rising velocity an increasing amount of accelerations comparable to putting down a carrying chair and higher are observed in the y as well as the z direction. However, as the sensor was directly mounted to the frame of the carrying chair and the functional model during experiments acceleration and jerk experienced by the patient are expected to be lower due to damping by the seat cushion. In addition, the functional model of the mechanism isn't equipped with any suspension, nor pneumatic tyres, which would reduce acceleration and jerk. Furthermore, a comfort oriented control of the mechanism, especially in the z direction could further decrease acceleration and jerk.

All things considered, the first concept proofed feasible, while expected strains for the patient remained within a common range. A comprehensive comparative study of the functional models of the best rated concepts is pending before a final concept will be chosen

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