DOI: 10.31534/engmod.2023.1.ri.02a
Original scientific paper
Received: 1.02.2022.

Numerical Modelling of Loads on the Structural Elements of an Innovative Mechanism Enabling Wheelchairs to Negotiate Stairs

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SUMMARY

This article presents a numerical study of the loads on the structural components of an innovative system designed to enable a typical wheelchair to negotiate stairs. Such a system is a structure of several levers moved in an appropriate sequence. An important aspect of the design described was that it should not be a completely new wheelchair structure, but merely a set of mechanisms which, when fitted under the seat, would enable the user to negotiate stairs and other obstacles arising from the difference in height. The numerical analysis of the wheelchair movement was performed using the MSC Adams software. On its basis, drives or actuators that could be used in the actual mechanism were also selected. The wheelchair structure and the device under analysis were designed using Autodesk Inventor.

KEYWORDS: *wheelchair; negotiating stairs; numerical load simulations.*

1. INTRODUCTION

Most people are unaware of the limitations people with mobility impairments face when moving around in their environment. However, for a person in a wheelchair, negotiating regular stairs is usually a big challenge, very often impossible to overcome on their own. Of course, it is true that the infrastructure around us is increasingly using system solutions of building special approach ramps or special lifts [1]. However, in reality, such special structures are often impossible to apply, especially in older buildings, built long ago. In addition, the dynamic development of microelectronics and mechatronics means that obstacle-capable wheelchairs or add-on systems that extend the functionality of a standard wheelchair are increasingly appearing on the market [2]. Among the most common solutions here is a system based on a tracked drive. The caterpillar mechanism is only used for climbing stairs. Such a solution is effective in operation but quite complex. The high weight of the tracked system can result in damage to the edges of the stairs. It should also be mentioned that the wheelchair moves backwards when going up the stairs, which is not always comfortable [3]. Another concept for such devices is multi-wheel mechanisms. The idea is to use wheel rotation relative to an axis other than the wheel axis [4]. An example of this type of solution was analysed by Lawn [5]. This design uses four sets of wheels, four wheels in each set. The front wheels are used to negotiate stairs, while a different set of wheels is used to manoeuvre on flat surfaces. The disadvantage of this solution is its large size. Mikołajewska et al. [6] indicate that such mechanisms can be characterised by additional functionality. Namely, they can have a 'lift' function, which allows you to reach for an object at height. Another widely used group of assistive devices is stair-climbing wheelchairs. They only allow you to climb stairs. These include various types of platforms and wheelchairs widely used in public places. Their undoubted advantage is their great versatility, as they can handle a wide range of wheelchairs. The disadvantages of this solution include the need for assistance from another person [7]. The last group of devices of this type that is gaining popularity in recent years is walking robots with the ability to overcome obstacles. An example of this type of solution is described by Ghani [8]. The distinctive feature of this robot is that it has two supports, each with two steering wheels. These wheels can rotate around their own axis and around the axis of the set. The advantage of such a concept is that steps of different heights can be negotiated. The disadvantages of this solution are the need for several drives and complex control. In addition to solutions that can be classified into a specific group, there are also solutions defined as special. An example is the “Terrain-Adaptive Quadru-Track” [9] wheelchair equipped with wheels with spring-loaded treads. It operates by causing the tread elements to flex when faced with an obstacle such as a staircase. This creates a support point for the wheel.

In summary, each of the solutions discussed has certain limitations. Therefore, the authors have attempted to design a wheelchair with a structure different from those presented. A characteristic feature of such a wheelchair should be the ability to negotiate thresholds and elevations, especially stairs.

2. RESEARCH METHODOLOGY

The aim of the project is to design and analyse a solution which is an adaptation of the classic wheelchair in an upgraded version making it possible to negotiate stairs with a slope angle of up to *41°*, i.e. those found in residential buildings. The design assumes a staircase width of *70 cm* and a single step width of *20 cm*. The basic dimensions of the wheelchair were also adopted. They are schematically shown in Figure 1. The dashed line shows a simplified outline of the seat that joins the individual elements together.

It was assumed that the designed mechanism would operate on the principle of a multi-lever system. In order to keep the smoothness of movement, each of the supports will end in a wheel with a diameter of *10 cm* (Figure. 1.). It was also assumed that the wheelchair would move forward when climbing stairs. Therefore, stabilising the wheelchair in a horizontal position will be done by extending the supports accordingly. It is therefore proposed to fit a supporting mechanism behind the large wheel of the wheelchair to ensure that balance is maintained when the rear of the lever is raised simultaneously with the large wheel.

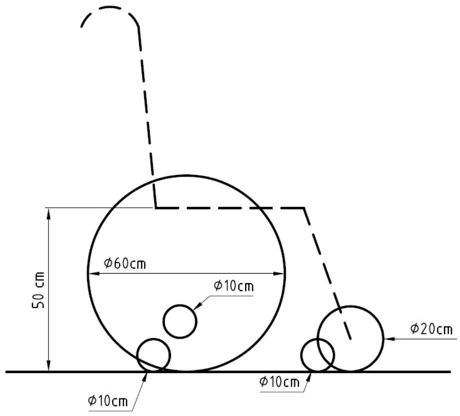


Fig. 1 *Diagram and dimensions of a classic wheelchair*

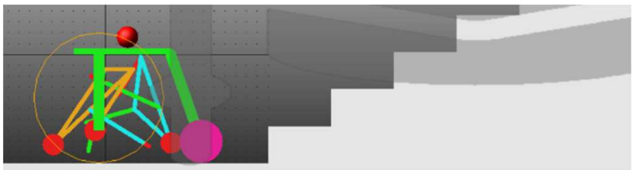
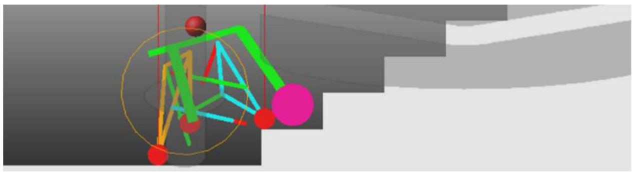
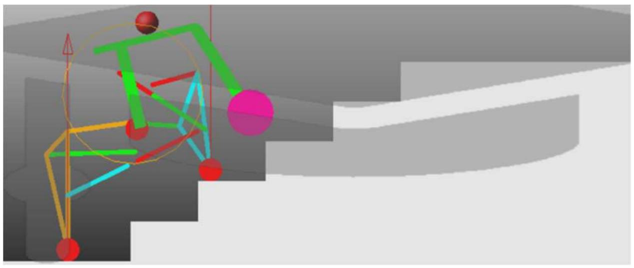
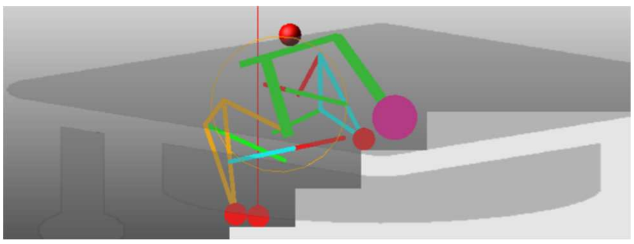
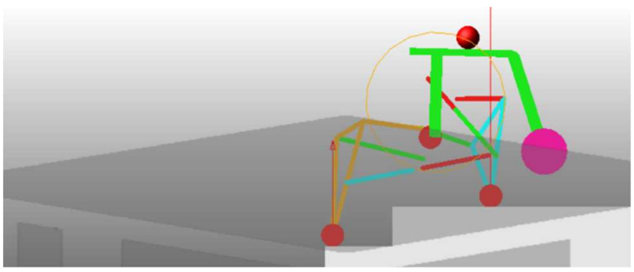
2.1 SIMULATION STUDIES OF THE MECHANISM STRUCTURE

The process of designing and simulating a mechanism to enable wheelchairs to negotiate stairs took place in several stages. First, the relative movements of the wheelchair and the trajectories of the supports whilst climbing the stairs were determined in the ADAMS software. MSC Adams (Hexagon AB [10]) software is probably the best-known environment in which it is possible to analyse the dynamics of vehicles, machines and mechanisms. After modelling the appropriate structures, taking into account masses, dimensions and any forces acting on individual elements, it allows us to determine the values of force courses, moments, displacements and accelerations occurring between parts and subassemblies during the operation of the device. The second stage of the work involved determining the kinematics of the mechanisms that are to realise the set trajectory of movement. For this purpose, the SAM software was used. SAM (Simulation and Analysis of Mechanisms) software is used to analyse motion and force in any mechanisms moving in a plane. These mechanisms are designed as a sum of basic mechanical elements such as beams or gears. The program allows you to analyse the trajectory of movement of individual points, as well as to optimize the mechanism, while imposing your own limitations. When designing a mechanism that could be attached to a classic wheelchair, the size of the wheelchair was a limitation. They have been selected in such a way that they do not interfere with movement on flat surfaces, while at the same time making it possible to overcome successive steps safely. Subsequently, the data extracted from the simulation models were processed and graphically presented in the MATLAB environment. Finally, the wheelchair solid with the lever mechanism was modelled in AUTODESK INVENTOR.

2.2 MECHANISM CONTROL SYSTEM

A SINENS SIMATIC S7-200 PLC was selected to control the entire mechanism that enables wheelchair users to negotiate stairs. This choice was dictated by the certainty and reliability of the device's operation and the possibility of extending it with additional modules. An additional aspect of choosing this particular controller was the need to ensure the safety of the wheelchair user. PLCs are characterised by operational stability and reliability, and this is particularly important in the case of equipment responsible for user safety.

Table 1 *Successive stages of wheelchair movement from the simulation*

No.	*Description*	*Simulation image*
1	*Initial position of the wheelchair. The wheelchair stands on the wheels on which it moves when travelling on flat ground.*	
2	*Start of climbing the stairs. The wheelchair is based only on the installed mechanism.*	
3	*The front wheel of the wheelchair and the front part of the mechanism are already on the first step.*	
4	*The front wheel of the wheelchair is at the height of the second step. At this stage, the person is most inclined.*	
5	*The difference in stairs between the wheels of the mechanism is 2 steps, but the mechanism is designed so that the person sits almost horizontally.*	
6	*All wheels both primary and secondary are located on the stairs. Further steps are climbed in accordance with the same procedure.*	
7	*Climbing the final step. The mechanism stabilises. The large wheel begins to rest on the ground. The secondary mechanism will then be raised allowing further travel.*	

3. ANALYSIS OF STUDY RESULTS

Simulation studies of the movement of the wheelchair while climbing the stairs were carried out by replacing each mechanism with the relative movement of the wheelchair. It is also assumed that the maximum inclination of the wheelchair should not exceed the inclination corresponding to placing the first pair of wheels of the wheelchair on the first step of the stairs. The next steps in the simulation are shown in Table 1. The red sphere visible in all the drawings above the wheelchair seat represents the wheelchair user's centre of gravity. Its mass of *90 kg* was used for the calculations. The analysis of the simulations carried out made it possible to determine the trajectories of movements that should be realised by the mechanisms of the lifting system. Figure 2 shows the support trajectories required to perform the programmed wheelchair movement. For the study, it was assumed that all trajectories of the designed mechanisms would be linear, which was the basic assumption considered during the synthesis of the kinematic chains. As can be seen in Figure 2, the final trajectory that was generated in Adams deviated slightly from the linear one. This modification is proposed on the basis of a simulation.

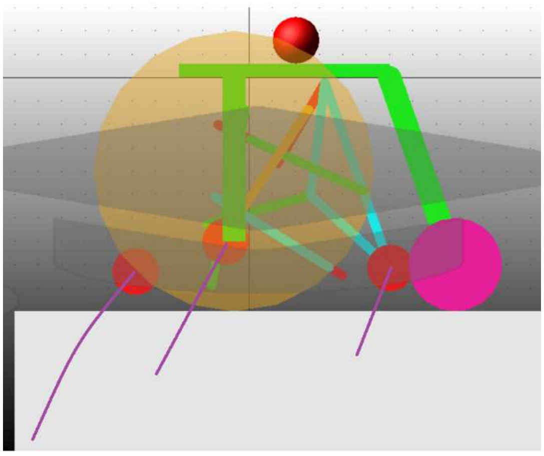


Fig. 2 *Support trajectories realised by the wheelchair lifting mechanism*

The kinematic system was synthesised using the intermediary chain method [11]. First, using the mobility of the individual elements, the mobility of the intermediary chain was determined. Then, the set of possible solutions was determined. The restrictions adopted were also considered. The occurrence of singular points was excluded in the mechanisms, i.e. arrangements where the force generated by the drive tends to infinity. After analysing a number of possible solutions [12], the kinematic scheme shown in Figure 3 was chosen.

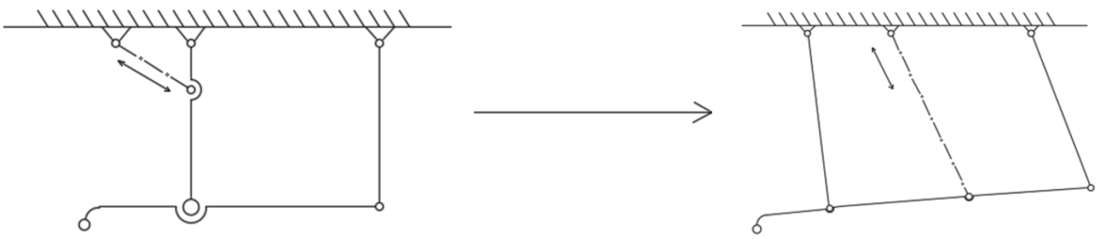


Fig. 3 *Selected kinematic diagram of the mechanism*

This diagram was chosen because of the simplicity of the design (presence of pivoting pairs only) and the limited space under the wheelchair seat. Each mechanism (front mechanism, rear mechanism and supporting mechanism) uses the same type of mechanism, adjusting the dimensions of the individual components accordingly.

The selection and optimisation of the dimensions of all components of each mechanism were carried out in the SAM software. The structures of the different mechanisms are shown in Figure 4.

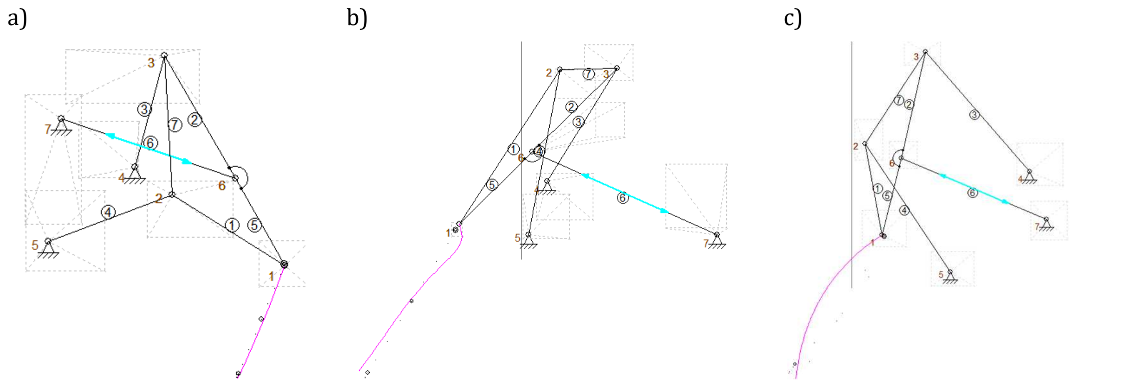


Fig. 4 *Result of the dimensional synthesis: a) for the front mechanism, b) for the rear mechanism, c) for the supporting mechanism*

To reduce friction in the kinematic pairs, rolling bearings were used. In order to select bearings accordingly, the load values at the nodal points of the structure were analysed. The next figures show the course of the variation of forces in kinematic pairs for the front mechanism (Figure 5), the rear mechanism (Figure 6) and the supporting mechanism (Figure 7) respectively. The numbers shown in the keys of the graphs presented refer to the numbering shown in Figure 4. Due to the discontinuity of the wheelchair contact and integration errors, spikes, which were removed using a median filter, were visible.

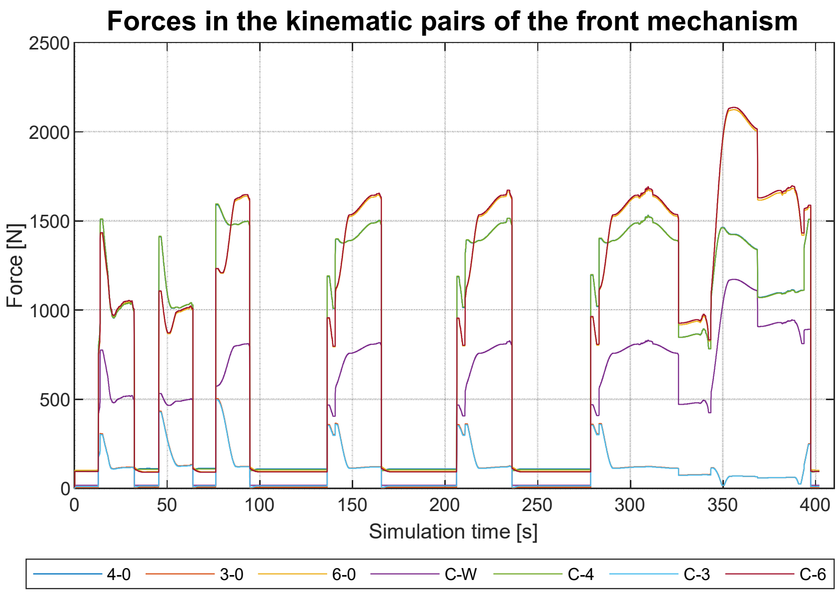


Fig. 5 *Course of load changes in kinematic pairs of the front mechanism. C – connector, a segment composed of elements 3, 4, 6, W – wheel, 0 – ground*

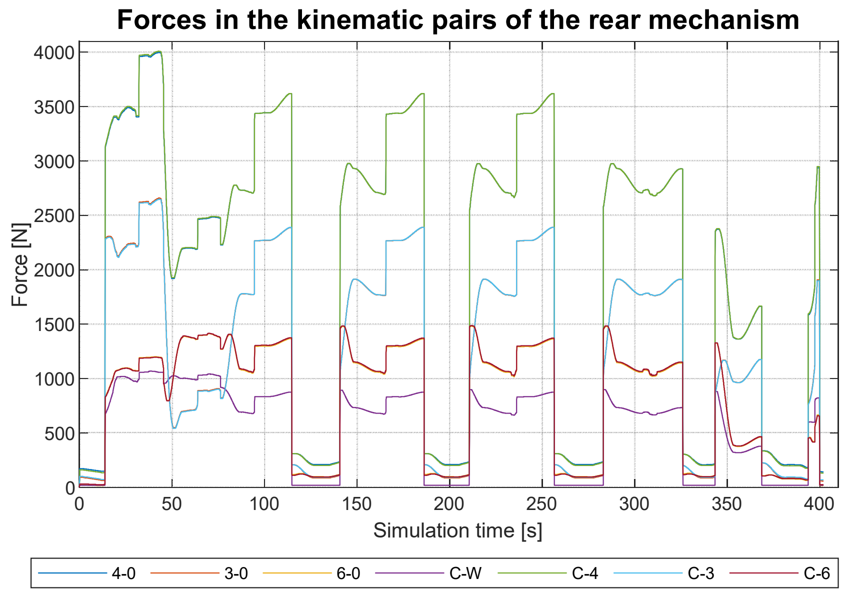


Fig. 6 *Course of load changes in kinematic pairs of the rear mechanism. C – connector, a segment composed of elements 3, 4, 6, W – wheel, 0 – ground*

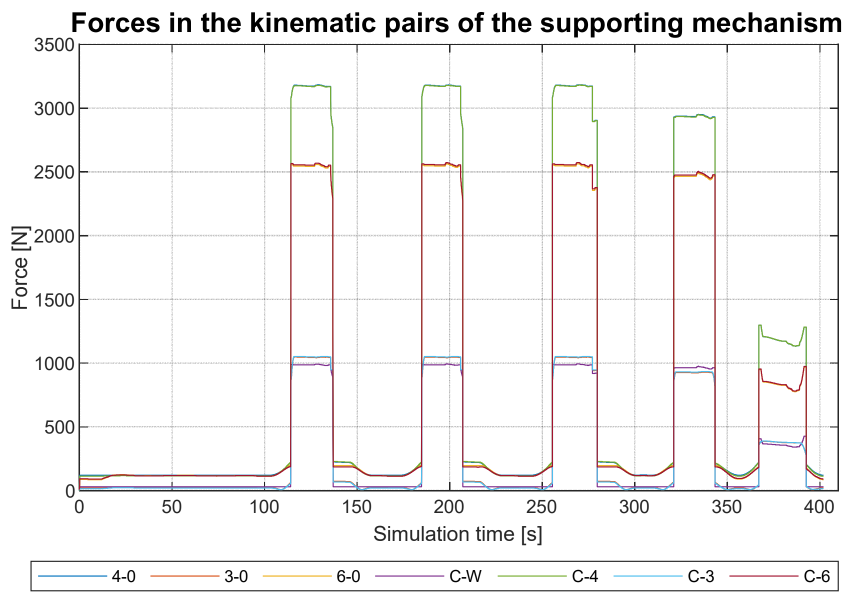


Fig. 7 *Course of load changes in kinematic pairs of the supporting mechanism. C – connector, a segment composed of elements 3, 4, 6, W – wheel, 0 - ground*

Due to the discontinuity of the wheelchair contact and integration errors, the generated graphs were filtered using a median filter created in MATLAB software. The analysis of the shown waveforms allows determining the maximum values of forces in particular kinematic pairs and selecting appropriate bearings. The numerical values of the forces thus estimated are summarised in Table 2. It can be seen that the maximum force is *4 kN*. In addition, the speeds in the pairs analysed are low. This is why HK1010 needle roller bearings made by FŁT were selected for each pair [13]. The scheme of this bearing is presented in Figure 8.

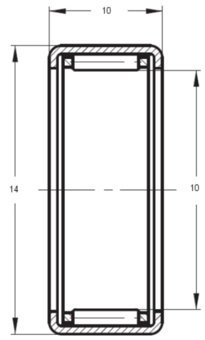


Fig. 8 *Scheme of HK1010 needle roller bearings made by FŁT [13]*

Table 2 *Maximum values of forces in kinematic pairs*

Mechanism	*Maximum dynamic load, [kN]*
Front	*2.2*
Rear	*4.0*
Supports	*3.2*

In order to select the appropriate linear drives, force diagrams and the extension speed of each actuator obtained during the simulation of the lifting mechanisms were generated. The waveforms of the forces acting on the actuators are shown in Figure 9. However, the extension speeds of the individual actuators are shown in Figure 10.

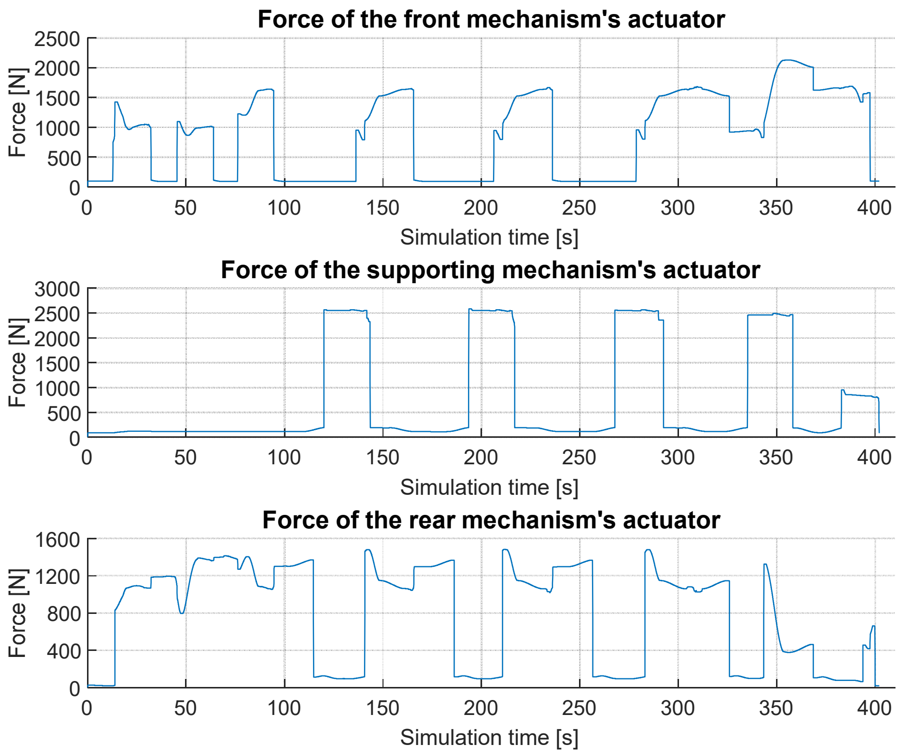


Fig. 9 *Load variations in the actuators of wheelchair lifting mechanism drive*

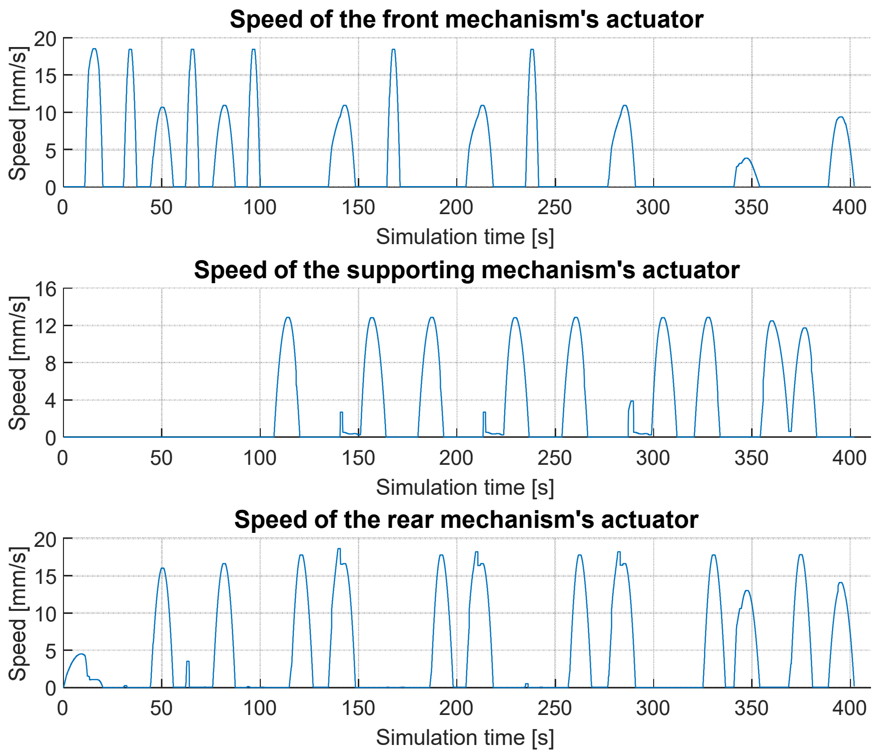


Fig. 10 *The course of changes in the extension speed of the actuators of the wheelchair lifting mechanism drive*

In order to provide adequate stability for the wheelchair and the wheelchair user when climbing the stairs, it was necessary to duplicate two of the three mechanisms – that is, the front mechanism and the rear mechanism. Consequently, two actuators were used to drive each of these duplicated mechanisms. At the same time, it was assumed that the support mechanism would be driven by only one actuator. Therefore, the maximum values for force, speed of movement and extension of the actuators were converted to refer to one linear drive. The calculated values are shown in Table 3.

Table 3 *Maximum values for force, speed of movement and extension of the actuators of the mechanisms per actuator*

	Front mechanism	*Support mechanism*	*Rear mechanism*
Number of actuators	*2*	*1*	*2*
Maximum force, [N]	*1100*	*2500*	*750*
Maximum extension speed, [mm/s]	*19*	*12*	*20*
Maximum extension, [mm]	*100*	*130*	*300*

This way of showing data made it easier to select actuators. As a result, two TMD02 actuators (model PTD-2406-4) from Duff-Norton [14], with a stroke of 4 inches (*101 mm*), were selected for the front mechanism. For the rear mechanism, the same two actuators were selected, only with a stroke of *12 inches* (*304 mm*). And for the supporting mechanism, the Electrac Pro actuator from Thomson Tollo with a stroke of *150 mm* [15]. Figures 11 and 12 present schemes of both proposed actuators.

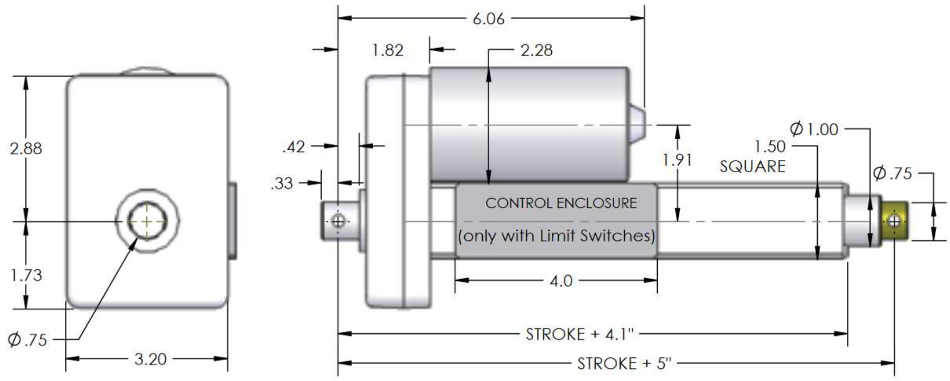


Fig. 11 *Scheme of TMD02 actuator. Dimensions in inches [14]*

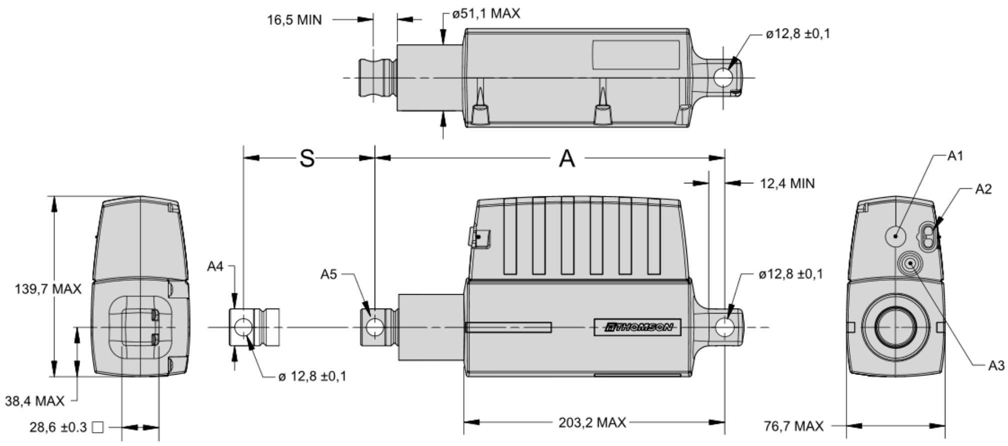


Fig. 12 *Scheme of Electrak Pro actuator [15]*

Movement of the wheelchair in the horizontal direction was provided by an electric wheel drive with a diameter of *100 mm*. The selection of drives was carried out based on a simulation of the course of moments and speeds of the driving wheels of the wheelchair (Figures 13 and 14). Two drives for the rear mechanism and one for the support were used to realise the progressive movement. According to the simulation carried out, the maximum required moments per drive were determined to be *0.7 Nm* for the support mechanism and *0.8 Nm* for the rear mechanism. Given the limited space under the wheelchair seat, the biggest constraint was the dimensions of the target drive sizes. Wheels with a built-in BLDC motor mounted in the hub were chosen as a proposal for the drive that could be fitted: HB4GS by UUMotor [16]. It is worth noting here that, although the analysis carried out was only simulation-based, kinematic analysis, as well as modelling, is a necessary first step to producing a new design and is widely practiced [17].

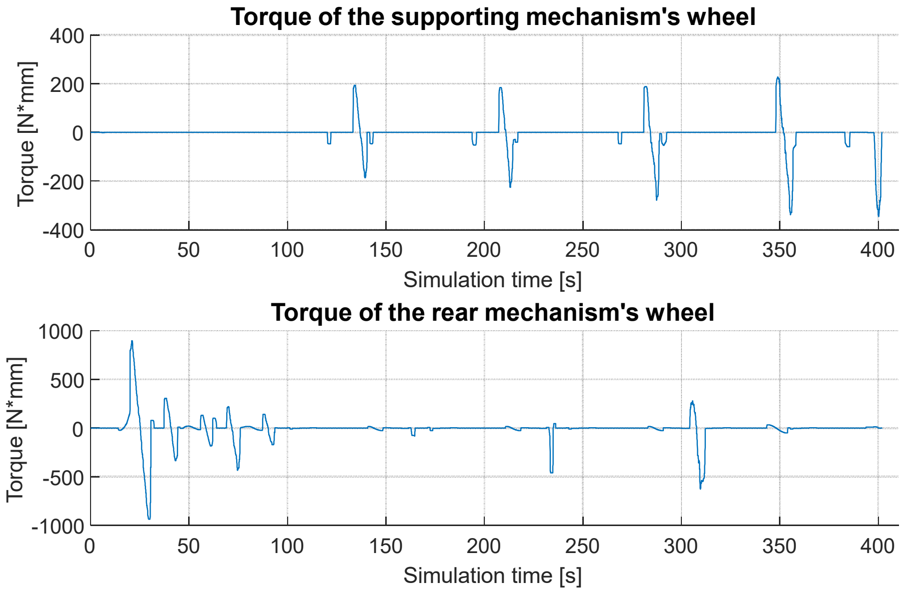


Fig. 13 *Torque variation on the drive wheels for straight wheelchair movement*

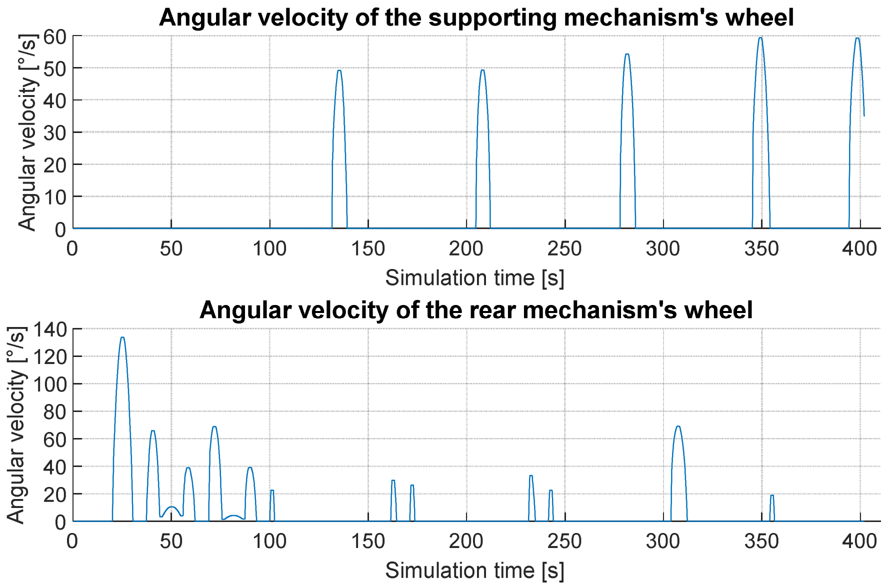


Fig. 14 *Speed variation of the drive wheels for linear movement of the wheelchair*

4. A MODEL OF A PROTOTYPE WHEELCHAIR INCLUDING A STAIR NEGOTIATING MECHANISM

A solid model of the entire wheelchair with all mechanisms analysed was made in the AUTODESK INVENTOR environment. The individual mechanisms extracted are shown in detail in Figure 15. The figure includes the actuators that control the movement of the mechanism, as well as the wheels at the end of the mechanism that touch the ground when moving up the stairs. The other 2 ends of each mechanism are attached to the wheelchair frame.

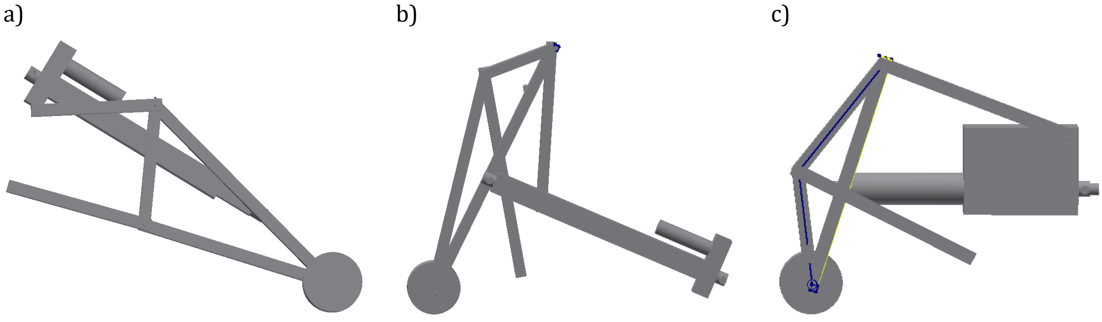


Fig. 15 *Solid model of: a) front mechanism, b) rear mechanism, c) supporting mechanism*

Drawing on the experience of other solutions of this type [12, 18], a similar system for attaching the designed mechanisms to the wheelchair structure was adopted. It was assumed that the load-bearing structure would be made of *10x14 mm* flat bars and that it would be permanently connected to the wheelchair. A model of the wheelchair with all the mechanisms used to negotiate the stairs is shown in Figure 16. It shows the case where all the mechanisms are spread out to their maximum length (Figure 16 a) and the case where all the mechanisms are folded so that the wheelchair moves on its wheels (Figure 16 b).

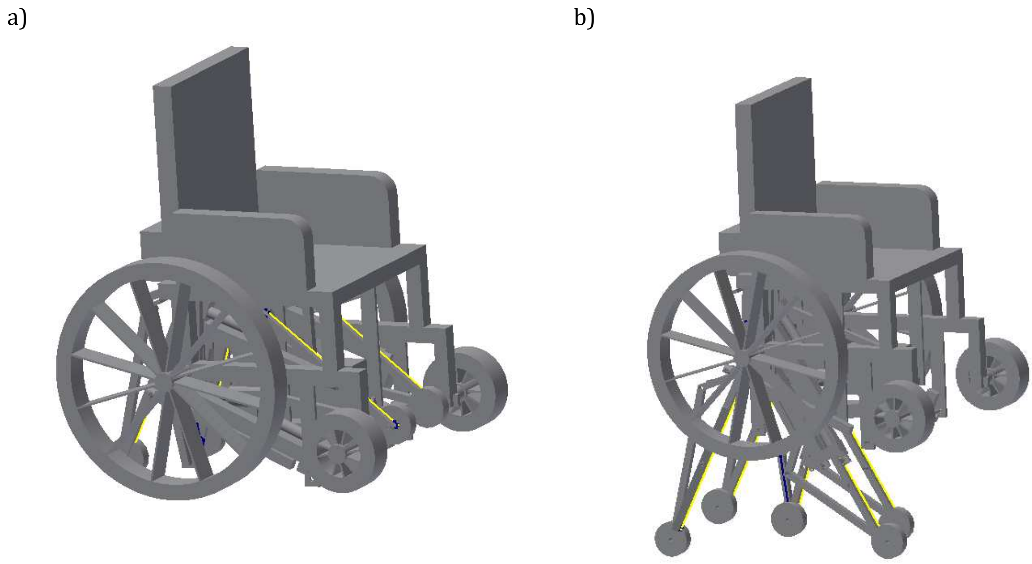


Fig. 16 *A side model of the wheelchair with the mechanisms: a) folded, b) spread out*

The lever structure of each mechanism would be made of aluminium sections with a square cross-section of *20x20 mm* and a wall thickness of *1.5 mm*. The bars were selected according to EN 10305 [19].

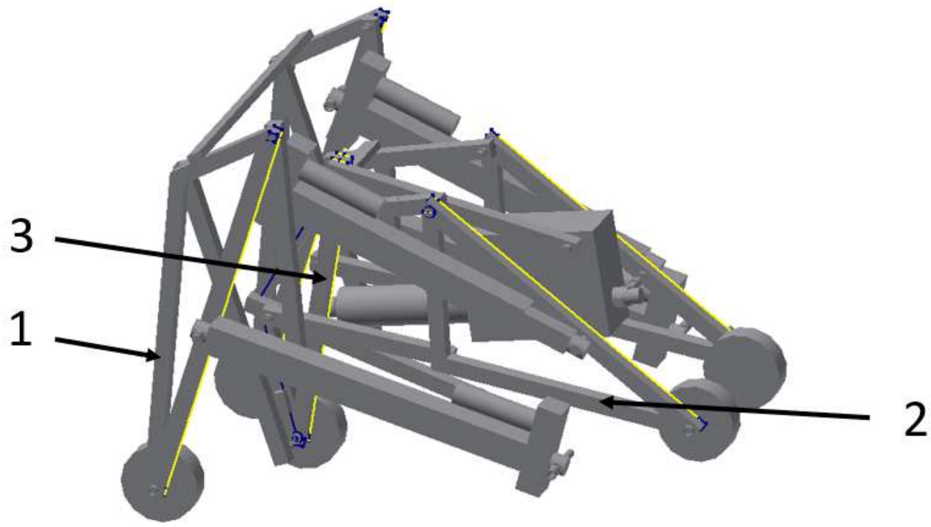


Fig. 17 *View of the mechanisms under the wheelchair, in the folded state; 1 – rear mechanism, 2 – front mechanism, 3 – mechanism of the supporting mechanism*

The power and control systems were placed "behind" the user, i.e. in the back of the whole wheelchair, which was also included in the model shown in Figure 16.

5. CONCLUSIONS

The analysis presented here has shown that it is possible to fit an additional mechanism into a standard wheelchair that could significantly facilitate independent mobility for people with mobility impairments. Using computer software, most notably the MSC Adams program, a set of mechanisms was designed and it was then demonstrated that fitting them as an attachment to a standard wheelchair would provide stable movement of a wheelchair user on stairs. The negotiation of 5 stairs was simulated, after which the entire ascent procedure is repeated. Thus, it would be possible to overcome them in any number. By analysing the individual forces and moments occurring at each stage, it was also possible to select suitable drives, bearings and actuators. Based on the modelling of the solid of the wheelchair together with the mechanisms and selected components, it was concluded that the proposed solution would fit under the seat of a standard wheelchair.

The most important advantages of the proposed solution include improving the mobility of people with disabilities and, consequently, increasing their independence. This is a proposal where there would be no need to manufacture a special wheelchair, just a suitable attachment to a standard wheelchair. Among existing solutions, this is a definite novelty. In addition, using the modelled solution, people with disabilities would be able to move freely on flat surfaces, and when approaching stairs or a curb, switch to the mode of climbing steps and overcome the height difference. It would be possible to automate the change of movement modes by attaching suitable sensors. The advantages of the proposed solution also include the fact that stairs can be climbed in the direction of walking and that the angle of the seat of the wheelchair does not exceed a difference of one degree, ensuring comfortable use.

However, certain disadvantages of the simulated solution should not be overlooked. First of all, the analysis simulated a wheelchair user weighing 90 kilograms. While there are no major doubts about its applicability for lighter people, there is a doubt about the wheelchair use for heavier people. According to the simulation, the dimensions of the stairs were assumed to be under the current standard, but it should be borne in mind that in older buildings the dimensions of the stairs may be different, including those that will not be safe to climb. Another doubt is people's trust in automatic control. It would be necessary to equip the designed wheelchair with a safety system that would activate the alarm in the event of an emergency and suspend the next steps. Nevertheless, the design presented could also be used with the assistance of another person who would not need to be trained or strong.

The manufacturing process of the mechanism would not be very complicated as it consists of widely available parts. Appropriate programming of the mechanism control would be only a one-time matter, with the possibility of uploading updates in the event of customer requests. The potential of the designed mechanism could also be extended, thanks to which the control could be adapted to some extent to non-standard dimensions of the stairs, for example in the user's home.

In the future, the authors intend to carry out an analysis of the application of the designed mechanism also for other dimensions of stairs and different human mass. Although the animation prepared showed that the proposed solution provides smooth movement, the movement could likely be optimised. At the final stage, the authors would like to make a prototype wheelchair with the mechanisms modelled and then carry out practical tests.

6. ACKNOWLEDGEMENT

We thank Hexagon for agreeing to use MSC Adams software free of charge in order to carry out and then publish the simulation results.

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