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A Mechanical Bed for Elderly Care to Assist while Standing, Sitting and Lying

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***Abstract*— In this article, a new design of bed for patient care is suggested, allowing hospital patients or people requiring home assistance to be able to get up on their own. This system is fully mechanical, which firstly reduces the risk of failure and the durability of the system, and secondly ensures autonomous operation without the need for a power supply. This system has three positions, the lying, sitting and standing position. A four-bar linkage controls the position of the bed, which is divided into three parts directly connected to the linkage, simplifying the kinematics of the bed. In addition to its manual operability, this innovative bed concept includes a safety system that locks the position at all times, preventing any sudden moves to keep the patient comfortable, while still allowing for a rapid position change.**

***Index Terms*— Mechanical assistance, Elderly care, Additive Manufacturing.**

I. Introduction

The population in Germany is ageing and this is referred to as demographic change [1], which is also accelerating thanks to the high standard of living in Europe. This problem is the same for all developed countries in the world [2], such as Japan or the United States. Beds to assist elderly people to get up, lie down or just sit down are under development and some models are even available for sale. On the market, two categories of beds that help patients to get up from the lying position can be distinguished. A first category includes beds that rotate around an axis that is located approximately in the middle of the bed [3]–[5], allowing the legs to be lowered and the seat and backrest to be raised. This motorized mechanism makes it easier for the person to get up, in a natural way, on the side of the bed. A second category of beds consists of lifting the patient using a mechanism placed under the bed, pushing the patient first into a sitting position, then lifting the patient by tilting the seat forward [6]–[8]. All the beds on the market or under development are motorized. The motors are of very high performance, so that they can lift a person's weight. As a result, the price of the motor increases, and so does the price of the bed. Since budget is one of the main concerns of most hospitals, a system without motors would be more affordable for professionals as well as for individuals. Another disadvantage of motors is the constraint of the power supply. The bed is not always easy to position next to a power socket because of its size and weight. Electrical wires on the floor are also dangerous, as the bed may roll over or the person may fall. Motor control also involves a noisy and slow mechanism. The rotation of the bed around the middle axis adds another waiting time before standing up. All the beds on the market offer a minimum of two poses, generally lying and sitting. The third pose is for most cases a slight change in the angle of the sitting position. This implies that the patient must use handles to get up completely, or step forward gradually on the equivalent of a high chair. The motion is not supported until the upright position.

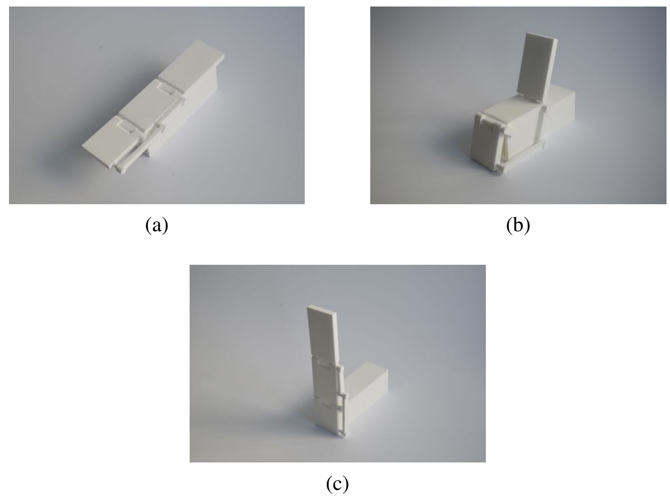

Fig. 1: Three positions of the bed in a chronological order: (1) lying position, (2) sitting position, (3) standing position.

In the first part of this paper, the principle of the mechanical bed is presented, illustrated by a first 3D printed prototype of the concept. The realization is explained in a second part and the components for actuation and security are developed in the third part. Finally, a conclusion provides an overview of the next steps in the construction process.

II. A FOUR-BAR LINKAGE TO COVER THE THREE POSITIONS

A. Concept

In order to achieve the three positions, sitting, lying and standing, the idea is to use a parallel four-bar mechanism. For each change of position, two in total, the fixing points of the base frame just have to be changed. The bars of the mechanism remain parallel to each other. This mechanism enables two positional changes by using only one actuation system. The concept is illustrated in Figure 3.

B. Design process

There are several phases in the construction of the fully mechanical bed. First, it is essential to notice that the parallel mechanism forces opposing bars to keep the same length. This reduces the parameters to be varied when deciding on the lengths of the mechanism. Then, the size of the bed depends on the size of the mechanism, so that the lower part and the upper part of the bed are activated together with the four bar mechanism. The design of the first 3D printed prototype is made with the SG-library [9]. After checking the feasibility of the parallel mechanism, a simulation of the system forces for movements 1 and 2 described in Fig. 3 is performed. Once the bed's functionality has been verified by simulation, the design is improved for the customer's needs. Indeed, the bed should not be too heavy to handle and the patient must always be in a safe position. The whole design process is illustrated in Fig. 4.

C. First prototype

The length of each component of the bed is arbitrarily chosen at the beginning, in order to test the movement of the bed and to understand the next issues to be considered

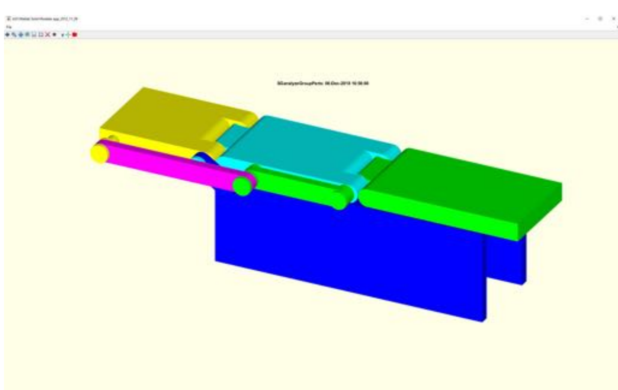

Fig. 2: 3D Design of the mechanical bed's first prototype.

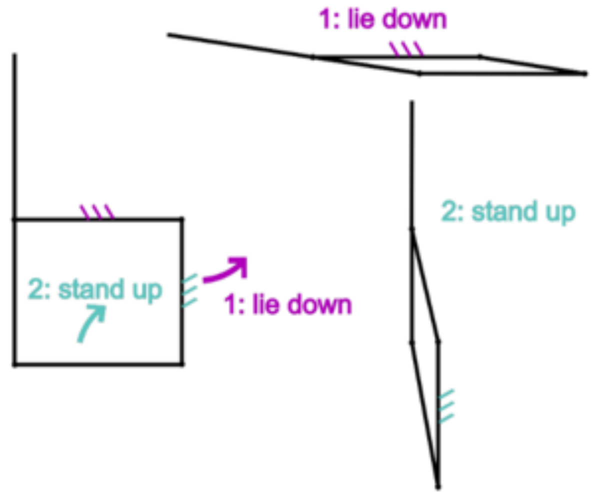

Fig. 3: The three positions of the four-bar linkage. On the left, the patient would sit on the chair. On the right, the two other positions correspond to two extreme poses of the four-bar linkage with a different ground.

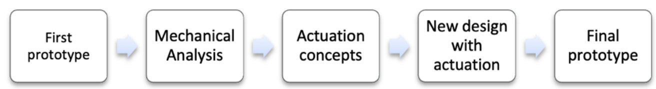

Fig. 4: Design process of the mechanical bed.

for actuating the mechanism. To carry out the three poses, a parallel four-bar mechanism is created in the SG-library. The model is illustrated in Fig. 2. The prototype was then printed in 3D using selective laser sintering with PA2200 [10]. This first print provides an opportunity to verify the feasibility of the project and to identify any necessary improvements. Although the result is promising, 3D printing also has its drawbacks. Indeed, the printed component is only movable when the joints are built with a certain tolerance. This alters the functions of the model, making the model unstable. In Fig. 1, the resulting model was captured in the three desired positions. The next step in the construction process is to establish the spring needed to transfer from sitting to standing position. For this purpose, this spring will be placed under the seat, as far as possible from the pivot axis, in order to reduce the required force. A weight system located on the pink part in Fig. 2 will also raise the back of the seat without using a powered system.

III. MECHANICAL ANALYSIS

A. Assumptions

The underlying four-bar linkage shall allow two different movements. On the one hand the movement from lying to sitting and on the other hand the movement from sitting to standing. As the mechanism remains the same for both movements, only one of the two movements is fully explained.

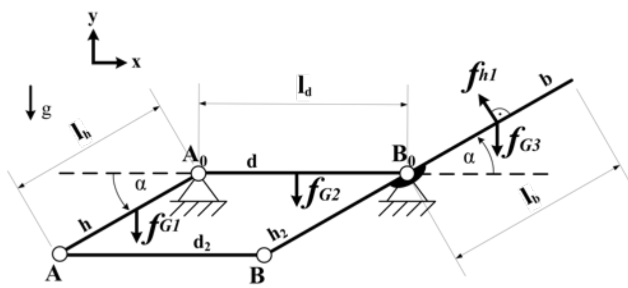

Fig. 5: Free body diagram for analyzing the first movement sequence.

The mechanism is considered to be operated with a force f_h that is either a human force or a counter weight or a spring. The primary purpose of this analysis is to define the forces required for both movements. The following properties are assumed for the calculation of the required actuation forces and torques:

- The seat height $l_h = 0.45\,\mathrm{m}$, the seat depth $l_d = 0.54\,\mathrm{m}$ are based on the human body dimensions [11]. The length of the backrest l_b is calculated from the total length of the bed from $l_{\text{total}} = 2\,\mathrm{m}$ to:

$$l_b = l_{\text{total}} - l_h - l_d, \tag{1}$$

- It is assumed that the total body weight is $m_{\text{total}} = 100\,\mathrm{kg}$. This load is segmented into three different proportions which correspond to the relative body mass proportions [12] [13] [14]:

$$m_1 = m_{\text{total}} \cdot r_h \text{ for } r_h = 24.5\%, \tag{2}$$

$$m_2 = m_{\text{total}} \cdot r_d \text{ for } r_d = 12\%, \tag{3}$$

$$m_3 = m_{\text{total}} \cdot r_d \text{ for } r_d = 63.5\%, \tag{4}$$

- The rods and bearings are considered without mass in the following scenario,
- For simplification, the mass segments are regarded as a point mass in the middle of the corresponding rods,
- The goal is a slow and smooth movement, therefore it can be assumed that the system is quasi-static [15]. The influence of moments of inertia and dynamic loads is therefore not taken into account.

B. From lying to sitting position

For the first movement (lying to sitting position), the surface of the seat must be fixed to the bed's frame. The joints A_0 and B_0 are therefore the corresponding ground links for this purpose. The angle α can vary between $0°$ (lying position) and $90°$ (sitting position) in respect to the horizontal axis. The equations for the determination of the searched variables are provided with the help of the free-body diagram (5). The forces in the joints, illustrated in (6), result from Newton's third law. Accordingly, $f^*_{Ax} = -f_{Ax}$ and $f^*_{Ay} = -f_{Ay}$ can be calculated. Furthermore, it is assumed that f_{h1} is always applied perpendicular to the middle of the backrest. Three equations can be established for each

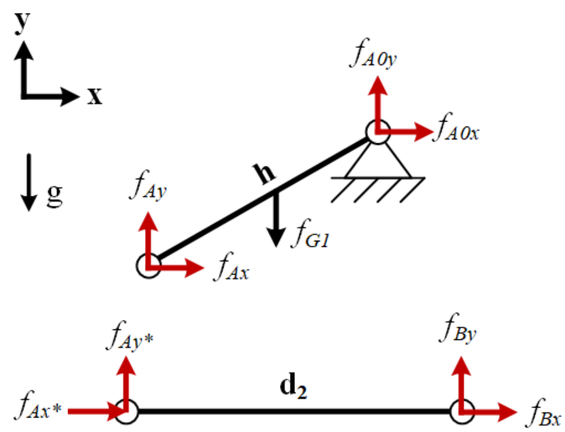

Fig. 6: Free body diagram of the rod h and d_2 for analyzing the first movement sequence.

movable rod of the planar four-bar linkage via the forces' equilibrium and the moments' equilibrium.

$$\Sigma F_x = 0 \tag{5}$$

$$\Sigma F_y = 0 \tag{6}$$

$$\Sigma M_z = 0 \tag{7}$$

The resulting nine equations can be generally described in a system of linear equations as follows:

$$\mathbf{A}\mathbf{x} = \mathbf{b} \tag{9}$$

The vector $\mathbf{x}$ contains all unknown variables. $\mathbf{A}$ and $\mathbf{b}$ can be derived from the above equations (6), (5), (7).

$$\mathbf{x} = \begin{pmatrix} f_{A0x} \\ f_{A0y} \\ f_{Ax} \\ f_{Ay} \\ f_{B0x} \\ f_{B0y} \\ f_{Bx} \\ f_{By} \\ f_h \end{pmatrix} \tag{10}$$

$$\mathbf{A}=\begin{pmatrix}1&0&1&0&0&0&0&0&0\\0&1&0&1&0&0&0&0&0\\0&0&-1&0&0&0&1&0&0\\0&0&0&-1&0&0&0&1&0\\0&0&0&0&1&0&-1&0&\cos(\alpha+\frac{\pi}{2})\\0&0&0&0&0&1&0&-1&\sin(\alpha+\frac{\pi}{2})\\0&0&\sin(\alpha)l_h&-\cos(\alpha)l_h&0&0&0&0&0\\0&0&0&0&0&0&0&l_d&0\\0&0&0&0&0&0&-\sin(\alpha)l_h&\cos(\alpha)l_h&(\frac{l_b}{2})\end{pmatrix} \tag{8}$$

$$\mathbf{b}=\begin{pmatrix}0\\f_{G1}\\0\\0\\0\\f_{G3}\\-\cos(\alpha)\cdot(\frac{l_h}{2})\cdot f_{G1}\\0\\\cos(\alpha)\cdot(\frac{l_b}{2})\cdot f_{G3}\end{pmatrix} \tag{11}$$

The gravitational forces f_{G1},f_{G2} and f_{G3} have been summarized in a single variable for simplicity and can be calculated by $f_{Gi} = m_i \cdot 9.81(\mathrm{m/sec}^2)$ for $i \in \{1,2,3\}$. In (7) the required operating force f_{h1} for the movement is plotted as a function of the angle α. The force f_{h1} is proportional to $\cos\alpha$ ($f_{h1} \sim \cos\alpha$) and has a peak value of $f_{hmax1} \approx 570.5\,\mathrm{N}$ in this scenario.

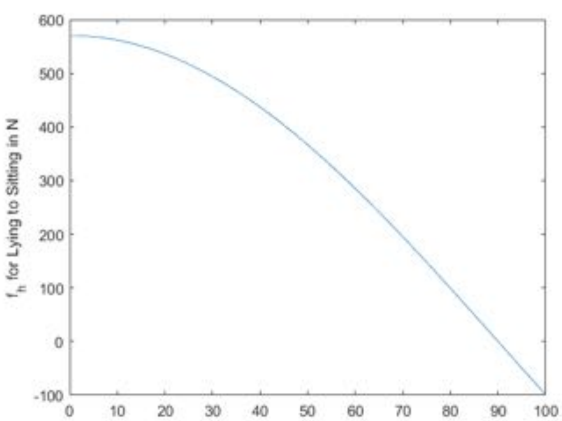

Fig. 7: Analysis of f_{h1} as a function of the angle α.

C. From sitting to standing position

The second movement sequence (sitting position to standing position) is made possible by changing the ground link in the four-bar linkage. In this configuration, h is fixed to the frame and the rod d can now be moved accordingly. The joints B_0 and A are also adjusted as shown in (8). Similar to the previous assumption, it is assumed in this case that f_{h2} is always applied perpendicular to the middle of the rod d. The calculation of the unknown variables is carried out analogously to the procedure explained above.

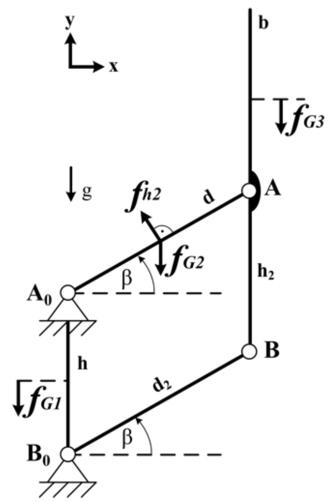

Fig. 8: Free body diagram for analyzing the second movement sequence.

In (9) the required operating force f_{h2} for the movement is plotted similarly as before as a function of the angle β. The force f_{h2} is proportional to $\cos\beta$ ($f_{h_2} \sim \cos\beta$) and has a peak value of $f_{hmax2} \approx 1468.2\,\mathrm{N}$. The angle β is taken between 0 and 90 degrees in the theory, but in practice, depending on the width of the rods, the maximum angle is not 90 but has a value of about 80 degrees. From this position, the patient must stand upright, unless he has not already done so before, by sliding along the seat, like other systems on the market.

D. Actuation concepts

The actuation of the system is supported by a counterweight for the movement from lying to sitting position and

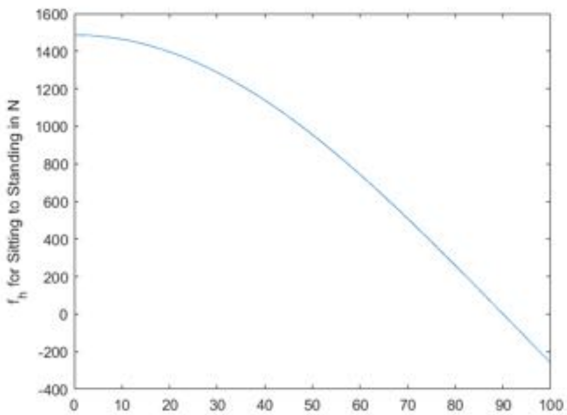

Fig. 9: Analysis of f_{h2} as a function of the angle β.

a gas pressure spring for sitting to standing position.

- The counterweight shall support the first movement sequence. It should be attached to the rod d_2 in such a way that it builds up a torque around the pivot A_0. This system is intended to minimize the required operating force f_{h1} so as to facilitate the movement process. In order to ensure that the second movement is not impeded conversely, the weight should be mounted axially displaced relative to d_2. Thus it is possible to shift the weight manually or automatically to a position where it doesn't apply any interfering forces or torques.
- The amount of operating force f_{h2} required for the second movement shall be reduced via a gas pressure spring, which is connected under the seat surface and fixed to the bed frame.

E. Security features

For the complete execution of both movements, it is necessary to change the frame of the four-bar linkage between the lying and sitting and sitting and standing positions. This frame's change requires additional mechanical elements. The joint A_0 is however always fixed to the frame, only the position of B_0 changes. This can be achieved by either securing the rod d or h to the frame. The chosen element for this task is the component in Figure (10), which represents a spring-loaded catch device [16]. Thanks to this element, movements are only possible successively, which ensures the security and stability of the system by locking the bed in the sitting position when the patient comes to sit from the standing position. In this first case, the rod d is then locked. The same system is used for locking the bed again but coming from the lying position. In this other case, the rod h is locked. Only one of the two devices must be manually unlocked to continue in either direction.

In order to prevent sudden unwanted movements, additional safety features must be added to the system. The idea is that the system should only be movable when an operating lever is manually actuated. Otherwise, all degrees of freedom are blocked. This is achieved by using a ratchet wheel and a corresponding pawl (Fig. 11), which are attached between the rods d and b so that rotation can be locked for both movement sequences. The idea at this point is to use this system to ensure that the bed is blocked in each position, while allowing the patient to get up or lie down at the desired speed. The mechanism is located on the side of the bed, also enabling the nurse to operate it.

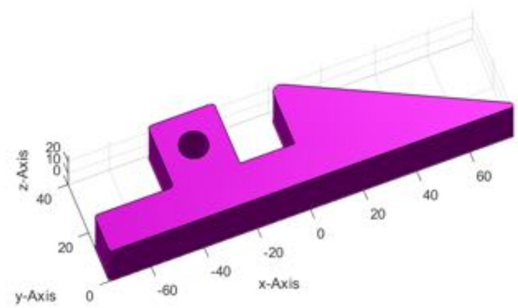

Fig. 10: Illustration of the locking mechanism for changing the frame.

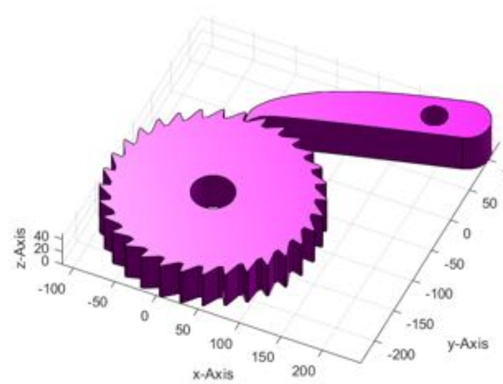

Fig. 11: Illustration of the ratchet-pawl mechanism used to prevent unwanted movements.

F. 3D prototype

In order to check the feasibility of the mechanism before building the real wooden model, a reduced version was designed in 3D. This model is presented in Figure 12. Activation systems such as gears and springs will then be added to the real model to make it more robust. This first 3D model is only for demonstration purposes.

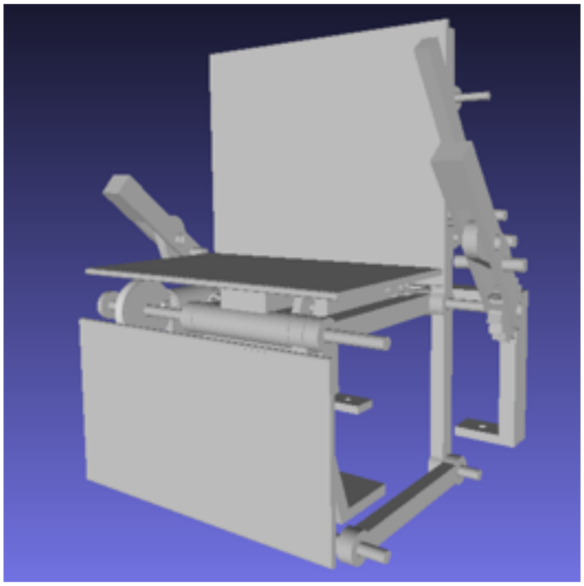

Fig. 12: 3D model of the bed, ready for printing.

IV. Conclusion and future work

The bed presented in this article is constrained by a four-bar mechanism fixed on the box spring. The first prototype printed in 3D shows the feasibility of the system. The mechanism analysis of the two desired movements describes the forces needed to help patients to stand up easily at home or in the hospital with the nurse's support. The mechanism operates without any motor, therefore, a spring and counterweights controlling the movement of the mechanism are added to reduce the actuation forces at the lever. Security features also lock the system at any time, permitting a controlled movement and facilitating the transfer from lying to sitting and standing position, in both ways. In a future work, the prototype will be printed in 3D again with its actuation and security systems. The future goal, after testing for the functionality of the 3D printed prototype, is to build a real bed in cooperation with a nursing home.

Acknowledgment

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