Design and Analysis of A Multifunctional Wheelchair

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Abstract: Based on existing designs of multifunctional wheelchairs, a new wheelchair designed with body posture adjustment function is proposed to satisfy the needs of the elderly and the disabled. This paper shows the overall design of the wheelchair and the establishment of its 3D model at first; then, the kinematics analysis of the wheelchair’s backrest adjustment mechanism, and verifying the smoothness of its reclining process with establishing a virtual wheelchair prototype for motion simulation in ADAMS; finally, finite element analysis of key components of the wheelchair to make sure their requirements of structural strength.

1. Introduction
Recently, the aging in China is characterized by the continuously growth of the elderly population, disability and chronic disease, empty-nesters and lost only-child old [1]. A report, published by the National Office for Aging in 2016, estimated that the number of disabled and semi-disabled elderly in China reached 40.63 million, of which about 10 million are severely disabled and mentally retarded [2]. The demands of life, health and rehabilitation care for elderly, disabled and demented people are significantly increasing [3]. However, the training of professional nurses, the systematic research and development of geriatric nursing projects are a gap in China [4]. Research shows that, for the elderly and the disabled who rely on wheelchairs in daily life, changing body posture regularly can relieve their physical fatigue. As a result, the occurrence of complications, such as pressure sores could be reduced [5]. To develop a wheelchair with function of automatic posture adjustment becomes a solution to the absence of professional nursing system. Compared with the traditional way of nursing, multifunctional wheelchairs do not require a large amount of work and long-term care [6]. In order to meet the requirements above, some medical equipment enterprises and relevant scientific research institutes have developed various kinds of old-age and disabled assistance devices, represented by combined nursing beds and multifunctional intelligent wheelchairs. The nursing bed is a multifunctional device that combines the mobile function of electric wheelchair with the nursing function of nursing bed, e.g. the Panasonic's robotic device [7], and the robotic chair/bed system E-bed [8]. The multifunctional wheelchair is capability of assisting patients in posture adjustment besides the basic mobility function. For example, Wy’East Medical Corporation invented a new multifunctional stretcher chair named Totalift [9], and Roger Bostelman et al. developed a multipurpose robotic wheelchair and rehabilitation device for the home [10]. The multifunctional wheelchair has excellent advantages such as compact structure, high flexibility and strong versatility, thus especially suitable for home care [11].
In order to provide efficient nursing care for the elderly and the disabled, a multifunctional wheelchair is designed in this research which can automatically adjust human body posture without any auxiliary equipment. The wheelchair can not only serve as a means of transportation for disabled people, but more importantly, it can prevent complications caused by long-term bedridden and sitting, reduce the work intensity of nursing staff, and improve life quality of the disabled.

2. Design Scheme
This designed multifunctional wheelchair not only fulfil the needs of the disabled, but also satisfy the requirements of stability and safety. Wheelchair has sitting and lying states, and usually it keeps sitting state during normal use. Patients can adjust their backrest and legs posture according to their own comfort needs. Standard height which is defined as 1750mm was used to compute size parameters of each part of the multifunctional wheelchair. The overall structure of the multifunctional wheelchair is shown in Figure 1. It is mainly composed of the base frame, the backrest mechanism, and the leg flexion and extension mechanism. These three parts bear most of the load during the transformation of the wheelchair. Backrest adjusting mechanism, leg flexing and stretching mechanism are used to adjust patient's body posture. The wheelchair mechanisms are independent and are not interfered with each other in the process of transformation.

3. Motion Analysis and Simulation of the Mechanism
The wheelchair should maintain stability during deformation to avoid discomfort, thus the speed and acceleration of each action mechanism are required to be smooth. The kinematics analysis and calculation of the backrest adjusting mechanism is taken as an example, and then the kinematics simulation analysis of wheelchair is carried out in ADAMS, with the movement speed of the linear actuator as the parameter, to verify the rationality of the mechanism design.
3.1. Kinematics Analysis and Calculation

The simplified structure of the main linear actuator part of the backrest adjustment mechanism is shown in Figure 2(a). It is correspondent to the part of Figure 1(a), called Two-stage linkage(a). In the model, AB indicates the shortest state of the main linear actuator while AB’ indicates the extended state, and BC stands for the main part of the two-section linkage. A denotes the connecting location of the frame and the linear actuator, B denotes the connecting location between the extended axis of linear actuator and linkage, and C denotes the joint connecting the frame of wheelchair base and linkage. The angular velocity of the linkage \( \omega_1 \) can be obtained using:

\[
\omega_1 = \frac{1}{\sqrt{L_1 + L_2 - (d_n + v_1t)^2}} \left[ -\frac{1}{2L_1L_2} \left( 2v_1^2t + 2d_nv_1 \right) \right]
\]  

Where, \( d_n \) is the original length of the linear actuator, \( v_1 \) denotes the movement speed and \( t \) denotes the movement time. \( L_1 \) denotes the distance between A and C, \( L_2 \) denotes the distance between B and C.

![Figure 2. Simplified schematic diagram of backrest adjusting mechanism.](image)

The simplified structure of the auxiliary linear actuator part of the backrest adjustment mechanism is shown in Figure 2(b). It is correspondent to the part of Figure 1(a), called Two-stage linkage(b). PE indicates the linear actuator. In the model, the arc chute is simplified to a fixed track arc \( \overline{BE} \) as the initial state, \( \overline{B'E} \) is the actual position state after the axis of the linear actuator extends. The angular velocity of the linkage \( \omega_2 \) can be obtained using:

\[
\omega_2 = \frac{2d_nv_2 + 2v_2^2t}{\sqrt{A^2 + B^2 - [d_n + v_2t]}}
\]

Where, \((x_P, y_P)\) is the coordinates of point P, the variable \( r \) denotes the radius of the arc segment. \( d_n \) is the original length of the linear actuator, \( v_2 \) denotes the movement speed of the linear actuator and \( t \) denotes the movement time.

3.2. Motion Simulation

A virtual prototype is built to carry out kinematics simulation analysis of the wheelchair. The reclining process of the backrest adjusting mechanism is controlled by the back main linear actuator and the back auxiliary linear actuator. The speed of the main linear actuator is 14 mm/s, and that of the auxiliary linear actuator is 4.1 mm/s, the motion time of both is 10 seconds. After the simulation, the angle change of backrest were measured, and the velocity and acceleration curves were output. It can be seen from Figure 3 that the backrest angle adjustment range is between 0° and 70°, and the
operation process is stable without mutation. According to the above simulation analysis, the design of the wheelchair backrest adjusting mechanism is reasonable and meets the expectation.

![Figure 3. Kinematics characteristic curve of backrest](image)

4. Finite Element Analysis of the Two-Section Linkage

Since the safety of the wheelchair is very important, static analysis of the two-section linkage was conducted, and the analysis results were compared with material strength standards to evaluate their safety. The two-stage linkage of the backrest are made of 6082 aluminum alloy, of which tensile strength is 310 MPa, the yield strength is 260 MPa and the elongation is 10% [12].

As a support and transmission part, the two-section linkage is subjected to the maximum load when the wheelchair is lying flat. Mass including the upper body, the backrest structure and the connecting parts act on the two-section linkage through the support points. The load distribution is shown in Table 1. ADAMS was used to calculate that the forces on the two-stage linkage are about 481N and 920N in the horizontal and vertical direction, respectively.

| Weight   | Remarks        |
|----------|----------------|
| Upper body | 440N above the pelvis |
| Backrest adjusting mechanism | 130N frame |
| Parts    | 7N slide rail   |
| Total    | 577N           |

The two-section linkage is modeled according to the original size and imported into the ANSYS Workbench for materialization. After setting the material properties, the mesh is divided, and finally the load and constraints are applied for finite element analysis. The number of grids and nodes of the linkage is 1166679 and 1743020 respectively. According to the analysis and calculation results in Figure 4 and Figure 5, the two-section linkage shape variable is 2.2 mm in the acceptable range; the maximum stress is 131.9 MPa, which is less than the ultimate stress of the material. Therefore, the structural strength of the component is qualified.

![Figure 4. Deformation cloud.](image)  ![Figure 5. Stress cloud.](image)
5. Conclusion
In this paper, a new multifunctional wheelchair with automatic postural adjustment is designed to satisfy the user's nursing needs and reduce the workload of nursing staff. The kinetic characteristic curve obtained through kinematics analysis and simulation indicates that the process of wheelchair backrest reclining is smooth and the rationality of mechanism design is verified. Furthermore, the results of finite element analysis about the key components of the wheelchair shows that the structure strength meets the requirements and the safety is excellent.

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