

Mechanical Design of a Wheelchair with Multi-Posture Characteristics

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Abstract—At present, an electrical wheelchair cannot meet the needs of patients, like paralyzed patients, who spend most of their time on beds. This paper presents a mechanical design of a wheelchair which can transform to a sitting, lying and standing posture. The standing posture can help patients to reach high place and do exercise. The patients can have rest on it when the wheelchair is lying. In addition, we modeled and simulated the mechanical structure to ensure the reasonableness of the design. Vector equation analytical method is used to conduct kinematic analysis to obtain accurate kinematic properties of structural parts throughout the posture change.

Keywords—rehabilitation; wheelchair; multi-posture; computer simulation

I. INTRODUCTION

According to the data communiqué of the second national sample survey of persons with disabilities, the number of people with disabilities of various types was about 85.02 million, which occupied the proportion of total population was 6.35% [1]. Meanwhile, China will usher the first peak of elderly population growth, the number of elderly people has exceeded 200 million in 2013[2]. The freedom and quality of life of both the elderly and disabled are severely decreased because their limb dysfunction restricts their daily lives. This not only brings a great nursing burden to their family, but also they have to turn to others for help [3, 4].

As an assistive means of transportation, wheelchairs are needed urgently by both elderly and disabled people. Manually operated and electrical wheelchairs with simple functions have become gradually unable to the needs of users. To provide elderly and disabled people with means of transportation with superior performance, and to help them improve their freedom of mobility and reintegration, wheelchair now tend to be more intelligent [5].

In the last two decades, most wheelchair studies focused on diversified control modes and additional functions such as standing and elevating etc.

Proposed aspects of control include voice [6, 7, 8], direction of the face [9], eye gaze [10], electromyography (EMG) signal from the neck and the arm muscles [11], EMG signal from the face muscles [12], wireless tongue-palate contact pressure sensor [13], eye-control method based on electrooculography

(EOG) [14], electroencephalography (EEG) [15] are proposed. Using these methods, it becomes easy for elderly and disabled people, to operate a wheelchair.

Some previous studies have shown the efficiency of additional functions. The standing function can help people with damaged spines to stand independently. This promotes body circulation, improves cardiopulmonary function, increases the calcium content of skeletons, and avoids bone loss, brittle bones, pressure sores, and other complications [16, 17, 18, 19]. Elevating functions are useful tools, which can allow users to independently lift wheelchairs to reach things at a high place or talk with others at the same eye level [20]. Lying functions can help people who have a physical dysfunction to move to or from bed without any assistance from attendees. As a result, it will reduce injury [21]. Of course, some previous studies attempted to develop a multifunction wheelchair which integrated one or more functions including standing, lying and other control modes [22, 23, 24, 25, 26, 27].

Many multifunction wheelchairs, such as those mentioned previously, improved quality of life to some extent. However, they actually have only several limited capabilities, e.g. they meet at the same time the conditions “effective control modes” and “different additional functions” only very occasionally. In addition, if patients want to get on to the bed from the wheelchair, or do some rehabilitation exercises, they need help from others. It is not only a waste of human resource but it also brings mental pressure to patients. They will gradually lose confidence. Therefore, it will be necessary to develop a versatile wheelchair with good performance and which will be easy to use. This paper presents the mechanical design of a multi-posture wheelchair.

II. METHOD

A. Mechanical Design and Kinematic Analysis

The mechanical structure of the wheelchair, wheelchair frame, seat, backrest, leg support and footrest are simplified as linkages which are connected as hinges. The actuators for lying and for standing can achieve posture change from sitting to lying and standing respectively. This not only simplifies the structure, but also is beneficial for the design of the control system. In addition, when considering safety in posture change, two anti-sway wheels are added under the footrest to make sure the center of gravity will not shift too much. The anti-sway wheels will not

touch the ground in the sitting posture and will not impact obstacles encountered by the wheelchair. Front driving wheels and universal wheels at the back also improve stability and safety in the lying posture. An actuator is added to expand leg support making patients comfortable when lying on it.

The structure of the multi-posture electrical wheelchair is shown in Figure I. In this structure, A, B and C are fixed points of the wheelchair frame; D is the hinge of seat and backrest; E is the hinge of actuator for standing and seat; the other side of actuator for standing and wheelchair frame are articulated in A; F is the hinge of seat and leg support; B is the hinge of the seat and wheelchair frame; G is the hinge of the actuator for lying and leg support; the other side of actuator for lying and wheelchair frame are articulated in C; G is the hinge of linkage and leg support; the other side of linkage and backrest are articulated in H; I is the anti-sway wheels which are fixed on the bottom of footrest; leg support and footrest are connected by actuator for expanding leg support and relative linkages. B, D, G, H and D, F, G, H constitute two parallelogram mechanisms, achieving the co-movement of seat, backrest and leg support in posture change between sitting and lying.

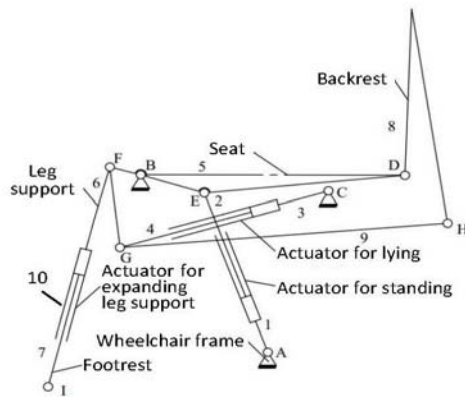


FIGURE I. STRUCTURE OF THE MULTI-POSTURE ELECTRICAL WHEELCHAIR

In the process of posture change from sitting to standing, the linear actuator for lying and the linear actuator for expanding leg support are locked and can be seen as a linkage. The linear actuator for standing is the driving link, and the whole structure can be seen as composed of seven moving parts and ten lower pairs. The DOF (Degree of Freedom) can be calculated according to the DOF formula as Eq. (1)

$$F = 3n - (2p_l + p_h) = 3 \times 7 - (2 \times 10 + 0) = 1 \quad (1)$$

In the equation above, n represents the number of moving parts, p_l represents the number of lower pairs and p_h represents the number of higher pairs. In this structure, A, B and C are fixed points on the wheelchair frame, and B, D, G, H constitute a parallelogram mechanism. Its working principle is as follows: the actuator for standing between A and E drives and spins the seat on B. The locus of E is an arc with B at its center, the radius in the length of BE; the locus of F is an arc with B at its center, radius in the length of BF; the locus of D is an arc with B at its center, radius in the length of BD. Under the action of actuator for lying, the leg support goes down; the locus of F is an arc with

C at its center, radius in the length of CG; H makes co-movement in the four-bar linkage to make sure that the angle of backrest is correct for patients. In addition, the anti-sway wheels are fixed to the bottom of the footrest. With the movement of the leg support, they will touch the ground to support the wheelchair and maintain a stable center of gravity assuring the security and stability of the posture change structure. The structure diagram for the standing state is shown in Figure II.

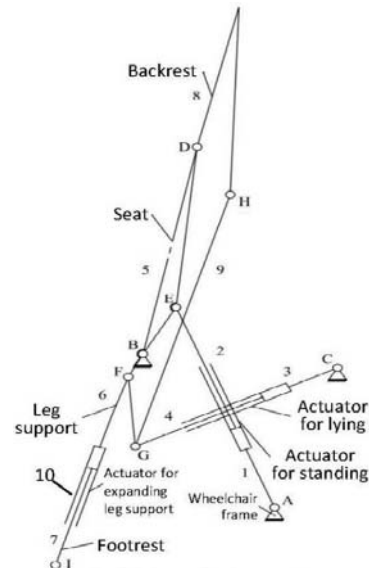


FIGURE II. STRUCTURE DIAGRAM FOR THE STANDING STATE

In the process of posture change from sitting to lying, the actuator for standing is locked, and can be seen as linkages, with the actuator for expanding leg support. Actuator for lying is the driving link. There are seven moving parts and ten lower pairs. The DOF $F=1$ according to the DOF formula.

In this structure, A, B and C are fixed points on the wheelchair frame. D, F, G, H constitute a parallelogram mechanism. Its working principle is as follows: actuator for lying between C and G drives and spins leg support on F. The locus of G is an arc with F to the central, radius in the length of FG. For the actuator for standing is locked, D, E and F are fixed. Under the action of linkage, backrest rotates around D. The locus of H is an arc with D as its center, radius in the length of DH. In addition, leg support and footrest elongate smoothly with the action of actuator for expanding making it more comfortable for patients to lie on. Structure diagram for lying state is shown in Figure III.

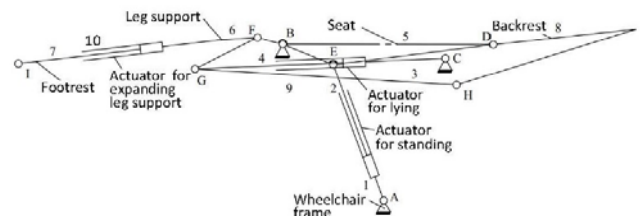


FIGURE III. STRUCTURE DIAGRAM FOR LYING STATE

In order to know whether the structure meets the

requirements of movement, the law of motion of the structure needs to be studied in the design process. In mechanical transmission, movement analysis of mechanical structure is the foundation of the analysis of the entire mechanical system. According to the movement of the driving link, displacement, velocity and acceleration of a specific point in the entire mechanical driving system can be obtained [28, 29]. As the graphic method is of low precision and time-consuming when analyzing motion mechanism, analytic methods and computer are used to help the analysis. Analytic methods can not only conduct high precision analysis, but can also draw a graph of the movement, helping improving design of mechanical design [30, 31, 32].

Because of the complexity of the wheelchair structure, vector equation analytic method is used in the analysis to obtain the precise kinematical characteristic of components in the process of posture change [33, 34]. The system of coordinates is established as shown in Figure IV. O is the origin of coordinate system. OA and OB are x axis and y axis of the coordinate system.

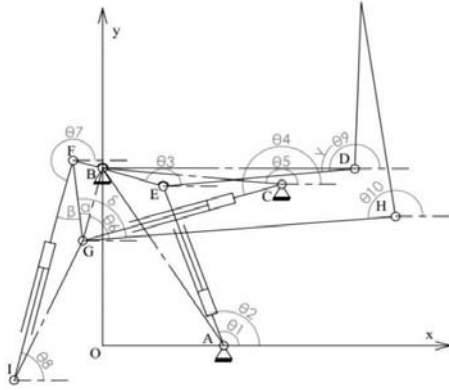


FIGURE IV. COORDINATE SYSTEM FOR CALCULATING OF PRECISELY KINEMATICAL CHARACTERISTICS

According to the relation between vectors, we can get Eq. (2):

$$\overrightarrow{AE} + \overrightarrow{EB} = \overrightarrow{AB} \quad (2)$$

Project vectors to x axis and y axis and we can get Eq. (3):

$$\begin{cases} x: |\overrightarrow{AE}| \cos \theta_1 + |\overrightarrow{EB}| \cos \theta_3 = |\overrightarrow{AB}| \cos \theta_2 \\ y: |\overrightarrow{AE}| \sin \theta_1 + |\overrightarrow{EB}| \sin \theta_3 = |\overrightarrow{AB}| \sin \theta_2 \end{cases} \quad (3)$$

Eliminate θ_1 and solve Eq. (4):

$$\theta_2 = \theta_3 + \arccos \left(\frac{AB^2 + EB^2 - AE^2}{2|\overrightarrow{AB}||\overrightarrow{EB}|} \right) \quad (4)$$

For A and B are fixed point on wheelchair frame, we can get Eq. (5):

$$\theta_2 = \pi - \arctan \frac{|\overrightarrow{OB}|}{|\overrightarrow{OA}|} \quad (5)$$

$|\overrightarrow{AB}|$ mentioned above is a known variable, so θ_1 can be calculated according to equations above.

θ_4, θ_5 and θ_6 can be calculated in a similar way.

According to the geometric relationship between the vectors, expressions can be determined for each position parameter of the structure:

$$\theta_7 = \pi + \theta_6 + \alpha - \beta \quad (6)$$

$$\theta_8 = \theta_6 + \alpha - \beta \quad (7)$$

$$\theta_9 = \pi + \gamma \quad (8)$$

$$\theta_{10} = \pi + \theta_6 + \alpha - \delta \quad (9)$$

α, β, γ and δ can all be calculated according to the law of cosines:

$$\alpha = \arccos \left(\frac{BG^2 + GF^2 - BF^2}{2|\overrightarrow{BG}||\overrightarrow{GF}|} \right) \quad (10)$$

When the position parameters of structural components are known, the motion trails of the hinges of components can be calculated. For example, position parameter of E as Eq. (11):

$$\begin{cases} E_x: -|\overrightarrow{EB}| \cos \theta_3 \\ E_y: |\overrightarrow{AE}| \sin \theta_1 \end{cases} \quad (11)$$

By computing the first derivative of Eq. (11) with respect to time, the velocity parameter equation of E can be obtained. By computing the first derivative of velocity parameter equation with respect to time, the acceleration parameter equation of E can be obtained. Kinematics parameters of other hinges can be calculated in the same way.

B. Three-dimensional Modeling and Kinematic Simulation

Firstly, connection relations between components of the wheelchair are defined as linkages, and kinematic pairs between linkages are defined as hinges. Secondly, relative kinetic parameters of driving links are defined. In the process of posture change between sitting and standing, the stroke of uniform motion in a straight line at a speed of linear actuator is set as 150mm, moving with uniform motion in a straight line at a speed of 7.5mm/s for 20s. In the process of posture change between sitting and lying, the stroke of linear actuator is set as 140mm, moving with uniform motion in a straight line at a speed of 7mm/s for 20s. In the meantime, the linear actuator for expanding leg support is set as 100mm, moving at a speed of 5mm/s for 20s. Then kinematic analysis is ready to begin. During analysis, a motion analysis calculator will stop, and causes of error will be shown within a pop-up dialog to help correct it if an error occurs in design scheme. Other, simulation animation will be shown after analysis. Interference can be detected in animation. Kinematic data can be obtained from

analysis results and can be presented in charts.

As can be seen in repeating the movement process, wheelchair model achieved posture between sitting and standing (Figure V), as well as sitting and lying (Figure VI). As shown in Figure VII, key components' horizontal displacement curve, with respect to the frame when changing posture between sitting and lying, can be obtained from getting angular displacement data of structural components in the results of analysis. As shown in Figure VIII, key hinges' displacement curve in x and y direction, when changing posture from sitting to standing, can be obtained from getting linear displacement data of hinges in the result. Also, key hinges' displacement curve in x and y directions, when changing posture from sitting to lying (Figure IX), can be obtained. The space motion path of structural components can be seen from linear displacement curve of key hinges. From the figures we can see that motions of hinges are smooth and the speed is gentle. This meets the requirement of wheelchair design. So it can be concluded that the mechanical design is reasonable.



FIGURE V. DIFFERENT POSTURE BETWEEN SITTING AND STANDING



FIGURE VI. DIFFERENT POSTURE BETWEEN SITTING AND LYING

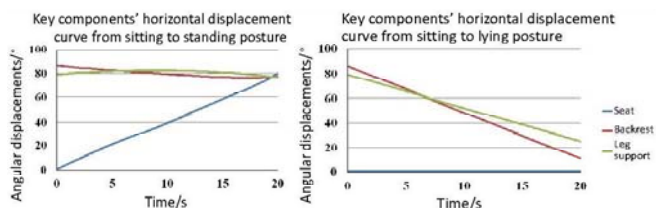


FIGURE VII. KEY COMPONENTS' HORIZONTAL DISPLACEMENT CURVE BETWEEN SITTING/STANDING AND SITTING/LYING POSTURE

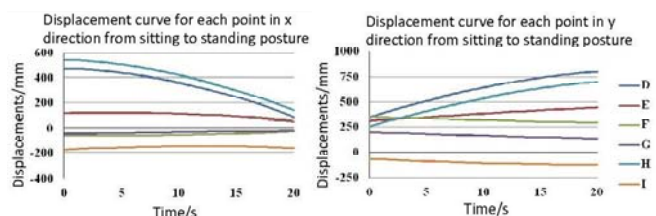


FIGURE VIII. KEY HINGES' DISPLACEMENT CURVE IN X AND Y DIRECTION FROM SITTING TO STANDING POSTURE

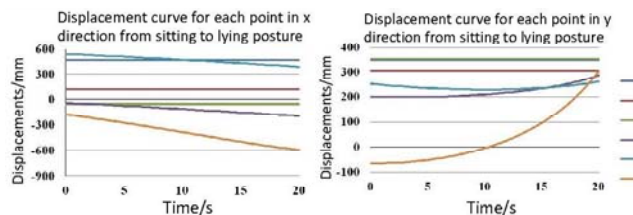


FIGURE IX. KEY HINGES' DISPLACEMENT CURVE IN X AND Y DIRECTION FROM SITTING TO LYING POSTURE

III. DISCUSSION

In the proposed mechanical design the basic structure has been determined by building and solving mathematical models, then we defined the design parameters of key structural components. The following kinematic simulation also has been done to verify the reasonableness of the parameters.

IV. CONCLUSION

In this paper, the mechanical structure of the wheelchair achieves fully posture change between sitting and lying or standing. In the process of posture change between sitting and standing, co-movement of footrest, seat and backrest is achieved through the four-bar linkage, and the anti-sway wheel will stretch out and touch the ground to support the wheelchair, ensuring the stability of the center of gravity. In the process of posture change between sitting and lying, co-movement of the footrest and backrest is also achieved through the four-bar linkage. Compared to some previous similar designs, this structure solves the problem that the footrest cannot extend, and increases comfort to the user experience while assuring stability of the center of gravity in the standing posture. The next research steps will include the implementing of the wheelchair plan, improvement of its mechanical structure based on the prototype.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial supports of the Shanghai Pujiang Program under grant numbers 16PJC063, the Shanghai young teacher training program under grant numbers ZZs115049 and Shanghai Engineering Research Center of Assistive Devices under grant numbers 16441905202. The authors wish to thank the authors of the references. There is no other potential conflict of interest relevant to this paper.

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