Human Standing-Up Trajectory Model and Experimental Study on Center-Of-Mass Velocity

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Abstract. In order to solve the rehabilitation training problem of sit-to-stand conversion for patients with lower limb dysfunction, this paper studies the human sit-to-stand conversion process, establishes the human standing-up trajectory model, and obtains the mass center and velocity equation of each joint. The optical motion capture system is used to measure the kinematics data of the transformation process of human sit-to-stand, which verifies the accuracy and reliability of the model. The results show that the vertical velocity is the most important factor that directly affects the process of sit-to-stand conversion, and the horizontal velocity is related to the stability of motion.

1. Introduction
Sit-to-stand transformation is a common movement of human body, which requires the cooperation of multiple muscle groups to ensure the balance in the process of standing-up [1]. Patients with low limb muscle strength and standing disorder have some difficulties in the sit-to-stand transition, requiring rehabilitation equipment to restore patients' standing ability. In recent years, with the aggravation of population aging, the research on the design and motion trajectory planning of rehabilitation robots have gradually increased. In 2012, Thomas c. Bulea from case western reserve university in the United States developed a vertical lift walker for assisting the sitting to standing conversion of people with lower limb muscle weakness. The disadvantage of this design is that the maximum lift provided by the spring must be less than the weight of the user, and the upper limb support weight is prone to secondary injury [2]. In 2014, Shi Xiaohua of Yanshan University designed a sitting/lying exoskeleton lower extremity rehabilitation robot to assist patients with lower extremity paralysis in sitting/lying posture rehabilitation training, and the feasibility of the design scheme of the robot is verified by clinical experiments [3-4]. In 2016, Xiong Tao of Guangxi University of Science and Technology carried out the trajectory planning of flexion and extension training for lower limb rehabilitation robot, determined the trajectory of linear and circular arc combination, and provided driving data for robot simulation [5]. In order to achieve and improve the effect of rehabilitation training, it is necessary to establish a suitable trajectory model of human sit-to-stand conversion, and to analyze the process of human sit-to-stand conversion in order to give a reasonable trajectory of rehabilitation equipment. Therefore, the trajectory and speed in the process of human sit-to-stand conversion are modeled and studied in this paper.
2. Establishment of human standing-up trajectory model

In order to ensure the rehabilitation effect, it is necessary to design the structure of rehabilitation assistant device according to the trajectory of human sit-to-stand transformation, however the process of sitting to standing transition is a compound movement process consisting of angular displacement of ankle joint, knee joint and hip joint. The sit-to-stand conversion trajectory is a composite trajectory composed of the angular displacements of each joint [6]. In order to facilitate the study of the motion law of each joint in the process of sit-to-stand transition of normal and disabled people, a typical model of human sit-to-stand transition trajectory should be established at first. Considering that the process of standing up and sitting down are two opposite movements, this paper focuses on describing the process of standing-up. The normal standing-up process of human body is a motion trajectory similar to a straight line or a circular arc, which is synthesized by the rotation motion of hip around knee joint and the rotation motion of knee around ankle joint. The purpose of the human standing-up trajectory model is to decompose the standing-up trajectory into the velocity trajectory of each joint [7]. The human body is regarded as a three-link model with three degrees of freedom. The three connecting rods represent the head-neck-trunk (HAT), thighs and crus of the human body from top to bottom. As shown in figure 1, the three-link model of human standing-up process can be divided into three stages: sitting posture, standing-up process status and complete standing state.

Assuming that the model is symmetrical on the sagittal plane, the coordinate system xoy is established by taking the ground position corresponding to the buttock center of gravity as the origin o, the horizontal direction is x, and the vertical direction is y. Suppose the center-of-mass coordinate of the ankle joint is \((x_1, y_1)\), the center-of-mass coordinate of the knee joint is \((x_2, y_2)\), the center-of-mass coordinate of the hip joint is \((x_3, y_3)\), the center-of-mass coordinate of the shoulder joint is \((x_4, y_4)\). Among them, \(l_1\), \(l_2\), \(l_3\) indicate the length of each crus, thigh and HAT segment, \(\theta_1\), \(\theta_2\), \(\theta_3\) represents the Angle between the lower leg, thigh, HAT and the horizontal direction. The motion trajectory of the center-of-mass of the knee joint can be decomposed into the composite motion of the angular velocity \(\dot{\theta}_1\) and the leg \(l_1\).

Therefore, the equation of the center-of-mass of the knee joint is:

\[
\begin{align*}
x_2 &= x_1 + l_1 \cos \theta_1 \\
y_2 &= y_1 + l_1 \sin \theta_1
\end{align*}
\]

(1)

Similarly, the equation of the center-of-mass of the hip joint is:

\[
\begin{align*}
x_3 &= x_1 + l_1 \cos \theta_1 - l_2 \cos \theta_2 \\
y_3 &= y_1 + l_1 \sin \theta_1 + l_2 \sin \theta_2
\end{align*}
\]

(2)

The equation of the center-of-mass of shoulder joint is:

\[
\begin{align*}
x_4 &= x_1 + l_1 \cos \theta_1 - l_2 \cos \theta_2 + l_3 \cos \theta_3 \\
y_4 &= y_1 + l_1 \sin \theta_1 + l_2 \sin \theta_2 + l_3 \sin \theta_3
\end{align*}
\]

(3)

The horizontal and vertical velocity of the knee joint can be obtained by taking the first derivative with respect to time \(t\) as follows:

\[
\begin{align*}
x'_2 &= -l_1 \theta'_1 \sin \theta_1 \\
y'_2 &= l_1 \theta'_1 \cos \theta_1
\end{align*}
\]

(4)

Similarly, the horizontal and vertical velocity of the hip joint is:
The horizontal and vertical velocity of the shoulder joint is:

\[
\begin{align*}
    x'_1 &= -l_1 \theta'_1 \sin \theta_1 + l_2 \theta'_2 \sin \theta_2 \\
    y'_1 &= l_1 \theta'_1 \cos \theta_1 + l_2 \theta'_2 \cos \theta_2
\end{align*}
\]

(5)

Through the human standing-up movement model, the motion equation in the process of standing-up was established, and the motion trajectory and horizontal vertical velocity of each joint in the process of standing-up were obtained. Similarly, the sitting-down process was the opposite of the standing-up process in the sit-to-stand conversion rehabilitation training.

\[
\begin{align*}
    x'_4 &= -l_1 \theta'_1 \sin \theta_1 + l_2 \theta'_2 \sin \theta_2 - l_3 \theta'_3 \sin \theta_3 \\
    y'_4 &= l_1 \theta'_1 \cos \theta_1 + l_2 \theta'_2 \cos \theta_2 + l_3 \theta'_3 \cos \theta_3
\end{align*}
\]

(6)

3. Experimental study on the trajectory of human sit-to-stand conversion

3.1. Test Equipment and Methods

At present, inertial sensor measurement method and optical system measurement method are mainly used to measure the trajectory of motion. Because of the high accuracy of optical system measurement, there will be no deviation due to the fixed mode of sensor in the measurement process. Therefore,
eight optical tracking cameras of Optitrack optical motion capture system in the United States are selected in the experiment, the capturing range is 3X3m, the pixel range is 1280X1024 (1.3 million pixels), the linear position error is 0.1 mm, and the sampling frequency is 240FPS. It has the characteristics of high speed and high precision. It captures the movement of key points of human body by infrared imaging, simulates the movement of human body in real time, and assigns it to the virtual role. The key points of motion trajectory capture of each part are shown in Figure 2.

![Figure 2](image)

Fig. 2. Key points of motion trajectory capture

For the patients, the upper and lower limb movement parts play an important role in the process of sit-to-stand conversion, so it is necessary to measure and analyze the kinematic parameters of the center-of-mass of each part in the process of sit-to-stand conversion. This experiment carried out sit-to-stand conversion trajectory test for healthy men aged 24 and height 178 cm, the standing-up process is shown in Figure 3.

According to figure 3 (a), the main weight of the human body is concentrated in the hip joint, with the body upright and slightly forward. Figure 3 (b) shows that the body tilts forward to make the center of gravity close to the knee joint in the horizontal direction, so as to reduce the load torque of the knee joint when standing-up, when the body tilts forward to the appropriate position, the thigh muscle will lift the body from the seat, this stage is mainly completed by the knee joint, and the knee joint will bear the maximum torque. Figure 3 (c) shows the body stretching after leaving the seat, while further moving the center of gravity forward, this stage is completed by the hip joint, knee joint and ankle joint. Figure 3 (d) shows that the body has basically finished standing-up at this point, with only minor adjustments to achieve stability.

3.2. Analysis of Test Results

In order to obtain the kinematic parameters of each part in the sit-to-stand transformation process more conveniently, several key points need to be analyzed when analyzing the process of human body sit-to-stand conversion. Because the upper limbs play a role of body balance and affect the distribution of the center of gravity in the process of sit-to-stand conversion, the shoulder joint of upper limbs is analyzed. And the lower limbs are related to whether the sit-to-stand conversion rehabilitation training can be completed, therefore, the lower limbs thighs are analyzed. Due to the sagittal symmetry of human body, left body parts were selected for analysis.

1) Analysis of shoulder joint trajectory
Fig. 4. Trajectory of shoulder joint in z and y directions

The kinematics parameters of shoulder joint were measured during sit-to-stand conversion, and the motion trajectory and speed of shoulder joints were obtained, as shown in Fig. 4-Fig. 6. Fig. 4 shows the trajectory of shoulder joint in z and y directions. In the process of standing-up, the shoulder height changes from 1.082-1.487 m, and the shoulder joint moves forward by 0.447 m, which is similar to the length of the thigh. In the process of sitting-down, the shoulder height changes from 1.492-1.076 m, and the shoulder joint moves backward by 0.411 m, with the center of gravity moving from the foot to the hip.

Fig. 5 is a curve of shoulder joint displacement in x, y and z directions varying with time. In the process of 2.392-3.242 s, the shoulder joint moves forward with the rise of the human body, with the increase of time, the shoulder joint enters a stable state. In the process of 6.558-7.892 s, the shoulder joint decreases with the body's reverse sits down movement, and finally enters the stable sitting posture and static.

Fig. 6 shows the curve of the motion velocity with time after fitting in the y and z directions of the shoulder joint. During standing-up process, the peak value of its horizontal velocity was 0.664 m/s, and the peak value of its vertical velocity was 0.511 m/s. During sitting-down process, its horizontal velocity peaked at 0.505 m/s and vertical velocity peaked at 0.449 m/s, but its direction was opposite to that of standing-up.

2) Analysis of thigh motion trajectory
The kinematic parameters of the key points in the thigh during the sit-to-stand transformation were measured, and the trajectory and speed of the key points in the thigh were obtained, as shown in Fig. 7-Fig. 9. Figure 7 shows the trajectory of the key points of the thigh in the $z$ and $y$ directions. During the standing-up process, the height of the thigh varies from 0.622 to 0.768 m, and the thigh moves forward from 0.335 m. During the sitting-down process, the height of the thigh varies from 0.753 to 0.612 m, and the thigh moves backward from 0.295 m.

![Fig. 6. Graph of the relationship between velocity and time in y and z directions of shoulder joint](image)

![Fig. 7. Trajectory of thighs in z and y directions](image)

Fig. 8 is a curve of thigh displacement in $x$, $y$ and $z$ directions varying with time. The first 2.308s thighs are in sitting position, as time goes on, the human body enters the standing state. The peak value of the key points of the thighs is 0.768 m, the thigh was in a stable state from 3.958 to 5.933 s, then the body moves in the opposite direction and sits down, and the thighs return to sitting position after 7.825 s.

Fig. 9 shows the curve of the motion velocity of the thigh with time after fitting in the $y$ and $z$ directions. During standing-up process, its horizontal velocity peaked at 0.352 m/s and its vertical velocity peaked at 0.166 m/s. During sitting-down process, its horizontal velocity peaked at 0.243 m/s and its vertical velocity peaked at 0.159 m/s, but its direction was opposite to that of standing up.
Fig. 8. Curve diagram of the relation between x, y, z direction displacement and time of thigh

Fig. 9. Curve of the relationship between velocity and time in y and z directions of thighs

4. Conclusion
1) Based on the analysis of the rehabilitation training process of sit-to-stand transformation, the trajectory model of human standing rehabilitation movement was established, and the horizontal and vertical velocity of each joint movement in the process of standing-up was obtained. The established model can describe the process of standing-up, providing a foundation for the design of lower limb rehabilitation training equipment and the research on rehabilitation training methods.
2) Based on the optical motion capture system, through the experimental study of the sit-to-stand conversion process of normal human body, the motion trajectory and speed of each part are obtained. Through analysis, it is concluded that the horizontal velocity fluctuation changes greatly, while the vertical velocity fluctuation changes little during the sit-to-stand transformation. Among them, during standing-up process, the horizontal velocity peak value of the thigh was 0.352 m/s, and the vertical velocity peak value was 0.166 m/s, the valley value of both velocities was close to 0.
3) By analyzing the velocity of the center-of-mass, it is concluded that: horizontal speed is the decisive factor to ensure that patients do not fall and can smoothly complete the rehabilitation training of sit-to-stand, while vertical speed is the decisive factor to complete the vertical standing.
Acknowledgments
This project is funded by Jilin Provincial Science and Technology Department Excellent Youth Talents Fund Project, No. 20190103009JH, the key technology research of lower limb standing rehabilitation training device and auxiliary force control.

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