

# Kinematic analysis of the human body during sit-to-stand in healthy young adults

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## Abstract

Sit-to-stand (STS) motion is one of the most important and energy-consuming basic motions in everyday life. Kinematic analysis provides information regarding what strategy or motion pattern is used by the healthy people, and through which, we can understand and obtain the law of the STS motion. The objective of this article is to study the law of STS motion through the experiment to determine a suitable description of STS motion in healthy adults, so as to provide a starting point and bases for future design and control of STS assistive devices.

Thirty healthy adult subjects participated in this study and carried out STS motion experiment of standing up naturally. The STS motions were recorded using a high-definition camera. The experimentally collected kinematic data and a link segment model of the human body were used to obtain the coordinates of joints and to calculate the coordinates, velocity, and momentum of center of gravity; the postures of human body during STS are also obtained. The relationship between human body parameters and motion parameters is analyzed by using Pearson correlation method.

The STS motion is divided into 4 phases; the phases are differentiated in terms of STS motion characteristics and postures, and momentum of center of gravity of human body. The main factors determining the differences in STS motion among individuals are horizontal distance between hip joint and ankle joint, lower leg length, thigh length, and the length of the transition period. The horizontal distance between hip joint and ankle joint is positively correlated with the duration from motion begin to trunk stops flexing forward ( $P = .021 < .05$ ), but not so with the duration from motion begin to the end of phase 2 ( $P = .15 > .05$ ).

The results suggest that when designing the sit-to-stand assistive devices, one should pay attention to the whole-body posture control in STS motion, such as the posture guidance of trunk and lower leg, and should carry out specific training according to different STS phases. Sit-to-stand assistive devices should provide the same horizontal distance between hip joint and ankle joint for different individuals during the STS motion. Transition period should be properly controlled, and the degree of freedom of the lower leg should not be limited.

**Abbreviations:** CM = center of mass, COG = center of gravity, D = horizontal distance between hip joint and ankle joint, H = height,  $L_1$  = lower leg length,  $L_2$  = thigh length,  $L_3$  = Trunk length, SAD = sit-to-stand assistive devices, STS = sit-to-stand, T = full sit-to-stand motion time,  $T^* = T_0$  to the moment when the trunk stops flexing forward,  $T_0$  = the moment of motion beginning,  $T_1$  = the duration of  $T_0$  to the end of phase 1,  $T_2$  = the duration of  $T_0$  to the end of phase 2,  $T_3$  = the duration of  $T_0$  to the end of phase 3, W = weight.

**Keywords:** center of gravity, momentum, posture, sit-to-stand assistive devices, trajectory, velocity

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## What Is Known

- According to the experimentally collected STS kinematic data of 30 subjects, the STS motion was divided into 4 phases; the main factors for the differences in STS motion were analyzed among different individuals, and the characteristics and laws of STS motion are summarized.

## What Is New

- This article presents the transition period in STS motion, and gives suggestions on how to choose a reasonable initial position for different subjects, which provides an important reference for the design and control of SADs, the patient care, and rehabilitation therapy.

## 1. Introduction

Sit-to-stand (STS) motion is one of the most important and energy-consuming basic motions in everyday life.<sup>[1,2]</sup> On average,

healthy adults perform approximately 60 ( $\pm 20$ ) STS motions every day.<sup>[3]</sup> As adults age, their sensory function gradually declines, greatly reducing their ability to balance.<sup>[4,5]</sup> People who have suffered cardiovascular and cerebrovascular diseases, heart failure, Parkinson disease, and diabetes mellitus<sup>[6]</sup> may also suffer from dyskinesia, which will lead to greater demand for muscle strength to deal with discordant hip motions, and distorted and even wrong motions during STS motion.<sup>[7–10]</sup> These problems prevent the normal and independent completion of STS motion.

To analyze and correct the wrong posture of patients with lower limb disorders during STS motion and evaluate the therapeutic effect, it is necessary to carry out STS transfer experiments for healthy adults to analyze and establish the kinematic laws and characteristics of STS.<sup>[11,12]</sup> Kinematic analysis provides information regarding what strategy or motion pattern is used by the healthy people, and through which, we can understand and obtain the rule of the STS motion. Based on the findings, clinicians can assess the body status of patients and implement treatment to enhance the use of a normal motion pattern and to eliminate the abnormal motion pattern for individual patients. Schenkman et al<sup>[13]</sup> studied the kinematics law and characteristics of the STS motion process of healthy adults, and divided the STS process into 4 phases, namely flexion momentum phase, momentum transfer phase, extension phase, and stability phase, and the clinical applications of the kinematics law and characteristics of the STS are discussed. The STS transfer has been divided into 4 phases, which is often referred to in the literature.<sup>[14,15]</sup> Analysis and understanding of each phase of the task of rising can assist the clinician in making the most appropriate decisions regarding intervention. Based on sagittal plane goniometric and force plate data from 20 normal subjects, Kralj et al<sup>[16]</sup> divided STS motion into 4 phases, that is initiation phase, seat unloading phase, ascending phase, and stabilization phase, respectively. They analyzed and summarized the motion characteristic of each phase, which is very important in clinical work for diagnosis of patients. Norman-Gerum and McPhee<sup>[17]</sup> developed a description of the STS motion by using experimental data from 15 healthy young adults, which can be used by clinicians and researchers to objectively assess if a motion is characteristic of healthy STS.

Sit-to-stand assistive devices (SADs) can safely help people with dyskinesia to complete STS motion and reduce the risk of injury to nurses.<sup>[18]</sup> Therefore, SADs play an important role in helping people with dyskinesia recover physical functions and complete daily activities. Mobot, a STS assistive robot, has been developed by University of Heidelberg,<sup>[19]</sup> which can calculate the compensation force by collecting the force condition on the handrail automatically, so as to carry out scientific rehabilitation training. Roman Kamnik et al<sup>[20]</sup> design a 3-DOF STS assistive robot, which can help people with dyskinesia to improve the coordination ability of the body by lifting and controlling the hip motion. Allouche et al<sup>[21]</sup> designed a kind of STS assistive device based on parallel mechanism, which uses elbow support and lifts trunk to complete STS motion, and it does not restrict the motion of lower leg and hip, so that the STS motion can be closer to normal posture. However, due to the lack of researches on the motion law and characteristics of STS transfer for SADs design and control, SADs could not complete STS transfer according to the natural STS motion law of human body. This leads to low human-machine cooperation and poor rehabilitation assistance effect, which may cause musculoskeletal damage, pelvic pronation, and muscle weakness in people with dyskinesia.<sup>[22]</sup>

To improve the performances and man-machine cooperation of SADs, it is very important to understand the kinematic law and characteristics of STS transfer in healthy adults. For example, to determine the degree of freedom, the motion trajectory, and the support mode of the SAD, we need to investigate the human body's STS transfer trajectory and the motion posture of different STS phases. To determine the control and driving mode, the motion speed, motion duration, and motion posture of the SAD, we also need to investigate and understand the motion trajectory, motion speed, time, and posture of the human body during STS. Therefore, to understand a STS motion more thoroughly and utilize the findings of STS studies for design and control of SADs, and evaluation of STS performance, it is important that STS motions are studied from law of motion and other perspectives. Diakhaté et al<sup>[23]</sup> studied the effects of different seat-thigh contact areas on STS speed in 17 healthy men and found a smaller contact area results in faster STS speed. Based on a review of a large number of STS motion studies, the key factors affecting motion characteristics of STS motion are seat height, the handrail, and the foot position.<sup>[24]</sup> Therefore, the initial position of patients using SADs is very important. The lower extremities and trunk muscles experience fatigue during repeated STS motions,<sup>[25]</sup> and the medial femoral, rectus femoris, and anterior tibial muscles are the 3 muscles with the highest activation rate during STS. The STS experiment of healthy young subjects was carried out to track and record point trajectories and the orientation of the trunk; the data of experiment were used to design STS assistive robots with a single and 2 degrees of freedom.<sup>[26,27]</sup> However, many kinematics researches of STS motion focused on clinical application, the development of rehabilitation training plan, and guidance of rehabilitation training, but the researches on kinematics law of STS motion for the design and control of SADs are less.

The objective of this article is to study the law of STS motion through the experiment to determine a suitable description of STS in healthy young adults. This will make it possible to quantify how a motion is representative of a healthy young person. In this way, this article provides a starting point and bases for future design and control of SADs. For this purpose, we carried out a detailed kinematics analysis of STS motion in subjects with different characteristics in specific body parameters (lower leg length, thigh length, height, and weight), and divided the STS motion into 4 phases. The kinematics characteristics and postures of each phase are obtained, and trajectories of joints of the subjects with different percentile human body were also obtained. We also calculated the center of gravity (COG) coordinates, barycentric velocity, and momentum curve of subjects during STS. Finally, the suggestions for the design and control of SADs are proposed.

## 2. Methods

### 2.1. Participants

We randomly selected 30 healthy adult male subjects to carry out STS motion experiment, and the subjects covered the population from the 5th percentile to the 95th percentile, the kinematic characteristics and the laws of motion obtained from these subjects are representative and statistically significance. The inclusion criteria were adult healthy subjects who have not had lower leg disease or injury. Exclusion criteria were patients with lower extremity leg disease, such as stroke, Parkinson disease,

**Table 1**  
Subjects' physical characteristics.

	Age, y	Height, cm	Body mass, kg	L <sub>1</sub> , mm	L <sub>2</sub> , mm	L <sub>3</sub> , mm
Mean	25.7	173.6	66.9	365.8	360.9	493.54
SD	±2.01	±5.58	±8.12	±23.36	±28.47	±26.94

and other symptoms. The body parameters of all subjects were collected before the experiment (Table 1). All subjects had no history of serious diseases. The Academic Committee of School of mechanical engineering, Tianjin University of Science and Technology, provided ethical approval for the study. The experiment was carried out from December 2018 through February 2019 at Tianjin University of science and technology. All subjects provided informed written consent to participate in the study.

## 2.2. Study design and procedures

This study was an observational study. To better obtain the motion trajectories of the subjects, we have made some restrictions on the STS motion of the subjects. Before the experiment, subjects were asked to wear tight clothing to reduce the chances of misalignment between body, clothing, and fat wobble, which may affect data collection. At the same time, during the experiment, subjects were required to fold their arms and tightly to the chest to avoid the influence of arm inertia. We limited all the subjects' ankles in the same position and fixed the seat height, we chose a 43-cm firm, back-less seat, and the position of the feet was the same width as the shoulder, other positions were not limited. Subjects were required to perform four STS exercises after full rest without turning head, body deflection or stopping halfway.

Low seat height can make STS motion difficult and abnormal STS motion.<sup>[28]</sup> To minimize the effect of seat height on subjects' motions, the seat height was set to not <85% of the lower leg length of all subjects. Four central markers were attached to the subjects, and 4 additional markers were set near each central marker to ensure measurement accuracy. A high definition camera (Canon, Japan, 1920 × 1080 pixel, 60fps/s) was used to collect the position of each central marker in the sagittal plane. All additional markers and 2 markers on the chair were used to calibrate the proportion and position of the central markers. In this way, the relationship between the position and time during the subject's STS motion was obtained (Fig. 1).

To simplify the motion model, we assumed that the STS motion is completed in the sagittal plane. The subjects were instructed to begin rising at the word "start" and ended with the subject's self-report when they fully stand. The 3-degree-of-freedom link segment model of the human body in the Cartesian coordinate system (X-Z plane) was established, for convenience, the position of the ankle joint was used as the origin of coordinates (Fig. 2).

The bias mainly comes from the subject, the researcher who carries out the experiment and the measurement process; we pay special attention to control the possible bias factors in the experimental process to ensure the accuracy and reliability of the measurement results.

## 2.3. Data analysis

We divide the human body into 7 segments, by using the body segment parameters,<sup>[29]</sup> as shown in Table 2, calculated the trajectory of COG.

We define the center of mass (CM) of each segment of the body with the following formula.<sup>[30]</sup>

$$\begin{aligned} X_{CM} &= X_p L_d + X_d L_p \\ Y_{CM} &= Y_p L_d + Y_d L_p \end{aligned}$$

where  $X_{CM}$  and  $Y_{CM}$  are the coordinates of CM;  $X_p$  and  $Y_p$  are the coordinates of the proximal end;  $X_d$  and  $Y_d$  are the coordinates of the distal end; and  $L_p$  and  $L_d$  are the percentages of segmental length from the proximal and distal ends, respectively.

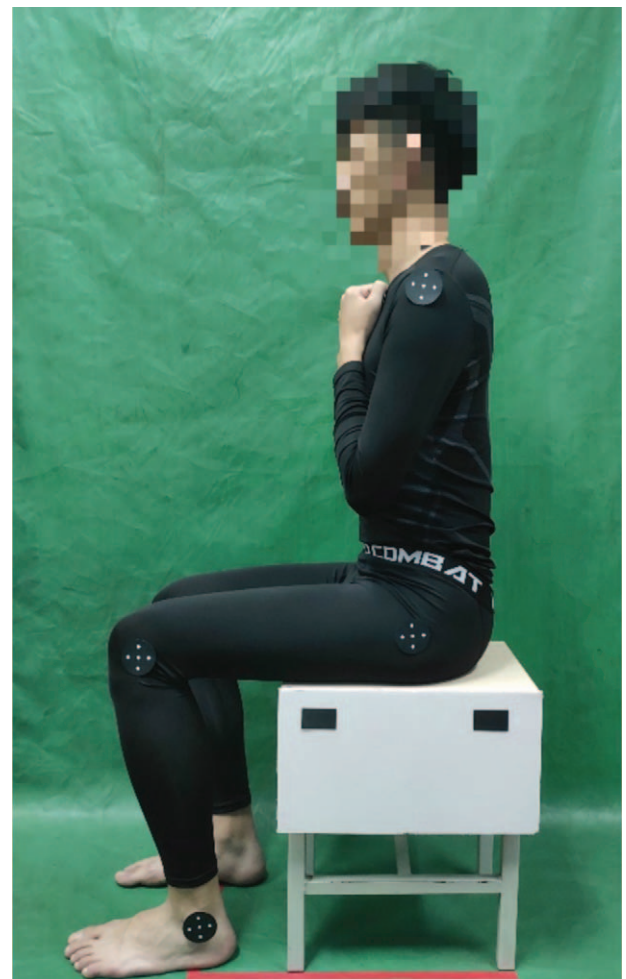


Figure 1. Sit-to-stand trajectory experiment.

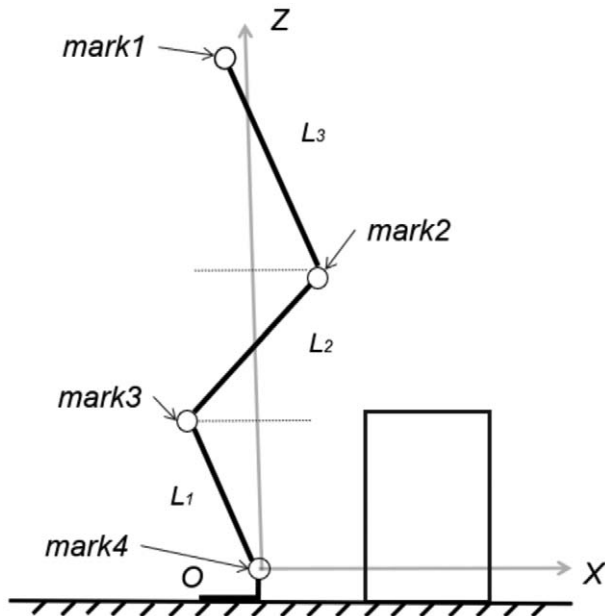


Figure 2. sit-to-stand motion model.

COG is the weighted average of the calculated CM of 7 segments, and was calculated by using the following formulae:

$$X_{COG} = \frac{\sum_{i=1}^7 m_i x_i}{M}$$

$$Y_{COG} = \frac{\sum_{i=1}^7 m_i y_i}{M}$$

where  $X_{COG}$  and  $Y_{COG}$  are the coordinates of COG,  $x_i$  and  $y_i$  are the CM coordinates of the  $i$ th segment,  $m_i$  is the mass of the  $i$ th segment, and  $M$  is the body mass.

We use finite difference method to calculate the velocity of the COG.<sup>[31]</sup> The central difference method was used to calculate the velocity:

$$v_i = \frac{S_{i+1} - S_{i-1}}{2(\Delta t)}$$

Where  $v_i$  are the velocity of the COG at time  $i$ ,  $\Delta t$  is the sampling interval of the data, and  $S$  is the linear position.

The forward and backward difference method was used to obtain a velocity at time 1 or  $n$ :

$$v_1 = \frac{S_2 - S_1}{\Delta t}$$

$$v_n = \frac{S_n - S_{n-1}}{\Delta t}$$

We use SPSS 23 (SPSS Inc, Chicago, IL) to analyze and process the data, and Pearson correlation analysis method is used to analyse the correlation between different body part lengths and STS motion characteristics parameters.

We screened all the data obtained and excluded the data with obvious errors to ensure accuracy of the results. As different subjects take different time to complete STS transfer, we normalize the time to calculate the mean value and standard deviation of the data. All curves are drawn by spline fitting using Origin 2018 (OriginLab, USA, Version 2018).

### 3. Results

#### 3.1. The STS phases division based on motion characteristics

The trajectories of the knee joint, hip joint, and acromion of each subject showed similar motion trends. The lateral iliac point (Mark3) trajectories are cycloid, the hip joint point (Mark2) trajectories are similar to an S-shaped, and the acromion point (Mark1) trajectories are L-shaped. In the STS motion, the lower legs and trunk of each subject have varying degrees of forward and backward flexion, which resulted in different STS trajectories. Thus, the STS motion was divided to facilitate the analysis of the differences between individuals and to improve SAD design and control.

The process of lower leg motion is complex, assuming that the face points forward, then there are 3 processes: forward flexing, backward flexing, and forward flexing again. We compared the STS motions among all individuals to generalize the rules of motion. To accomplish this, except for the first phase, we considered the moment when the direction of the lower leg changes as the demarcation point for dividing the phase. Thus, the STS motion is divided into the following 4 phases: the initial, balancing, rising, and the stable phases (Fig. 3), corresponding to phases 1 to 4 respectively. Through the division of phases, we obtain the time-consuming proportion of each phase of all subjects in STS motion, and the motion process is shown in Figure 4.

The STS motion characteristics and postures of human body in different phases are described as follows:

Phase 1: The motion is characterized by forward rotation of the trunk until the hip leaves the seat, while no obvious motion in other parts of the body.

Phase 2: The motion characteristic is that the hip leaves the seat, the whole body rotates forward, and rises with the ankle joint as the center, and the lower leg stops flexing forward at the end of this phase.

Phase 3: The rising phase is the most time-consuming and the phase of the greatest difference in position change. The motion is characterized by the backward flexion of the lower leg until it stops. The X direction displacement of Mark1 decreases, the hip

**Table 2**  
The body segment parameters.

Body segment	Segment definitions		Segmental mass/total body mass (%)	CM/segment length (%)	
	Proximal end	Distal end		Proximal	Distal
HAT	Head	Spine-base	61.31	54.9	45.1
Thighs	Hip	Knee	14.19	45.3	54.7
Shank	Knee	Ankle	3.67	39.3	60.7
Feet	Ankle	Foot	1.48	48.6	51.4



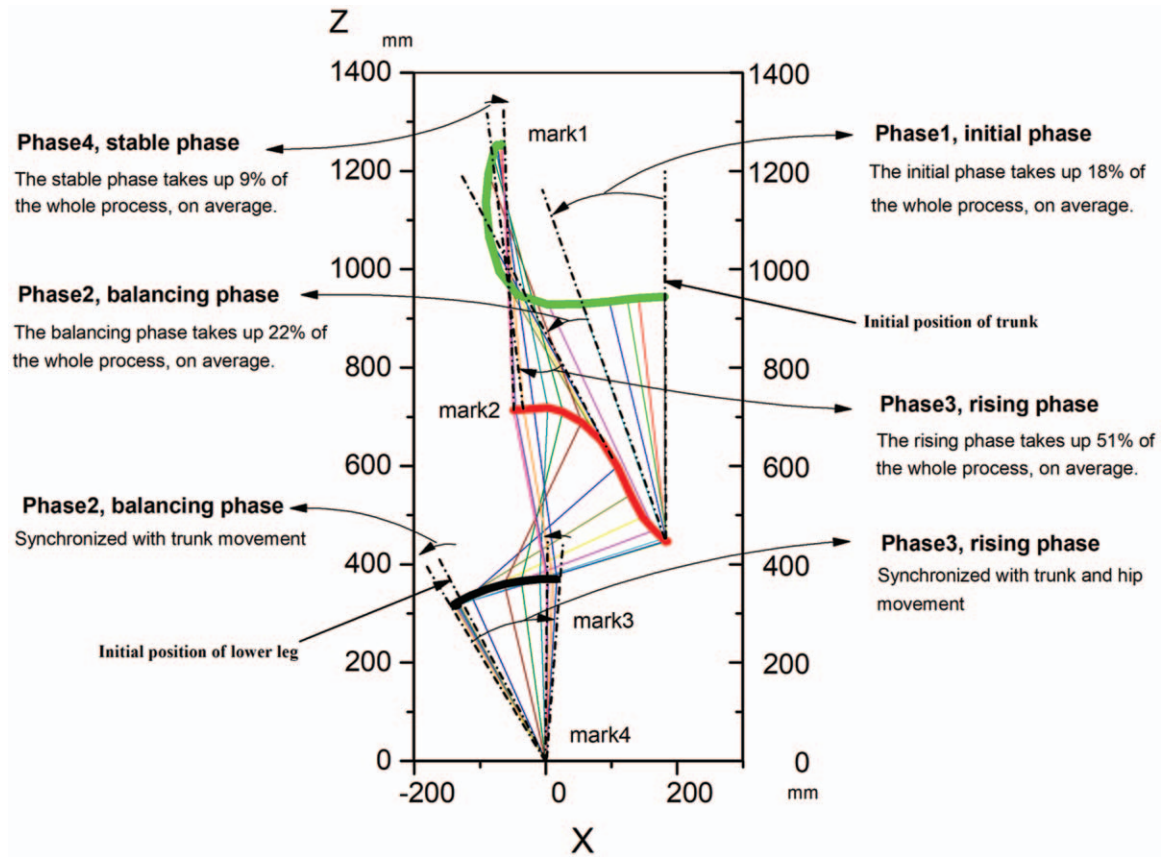


Figure 3. Schematic diagram of division principle.

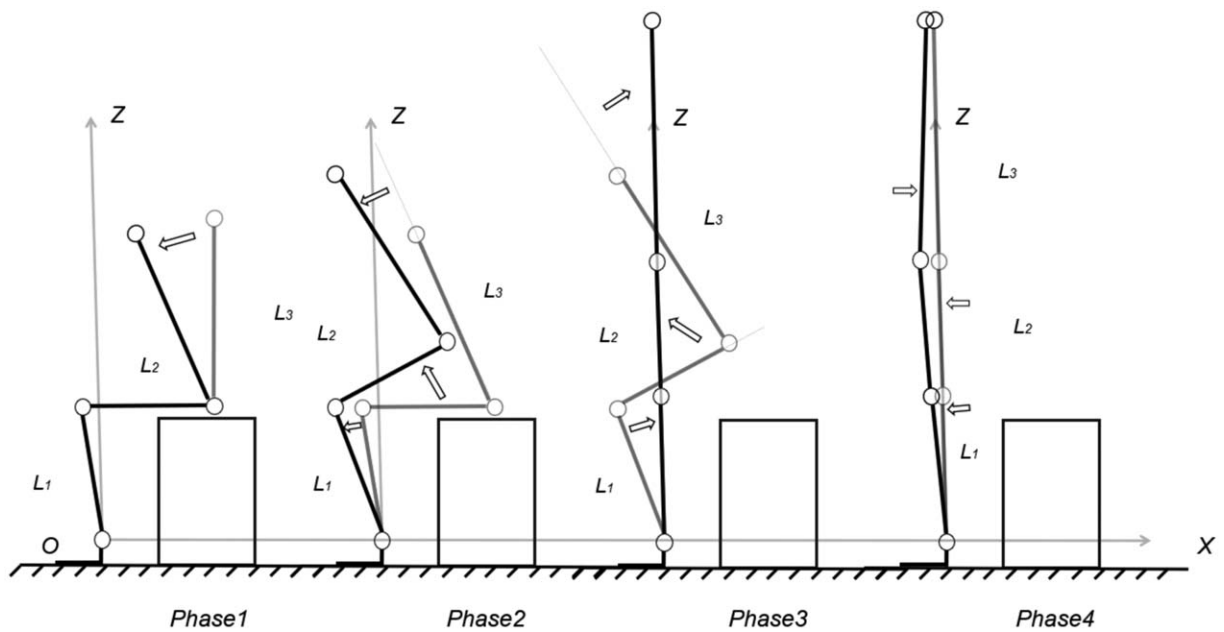


Figure 4. Stage process diagram.

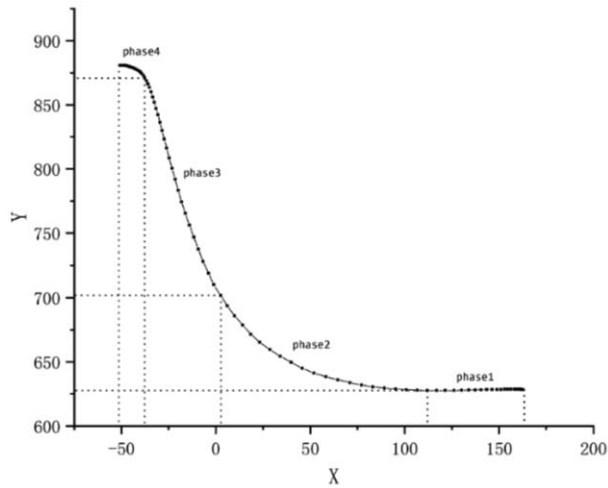


Figure 5. The center of gravity trajectory.

joint motion is dominant, and the trunk moves upward (see Fig. 3 and Fig. 4).

Phase 4: The motion is characterized by the trunk and lower leg assuming an upright position after the completion of the third phase. The lower leg and thigh flex forward again simultaneously, and the position of the Mark2 continues to move forward slightly as the displacement of Mark1 decreases. It is noteworthy that most subjects reported the end of the STS motion at a time when Mark1, Mark2, Mark3, and Mark4 were not on the same vertical line, and Mark2 was positioned relatively forward (see Fig. 3 and Fig. 4).

### 3.2. STS motion division based on momentum change and the trajectory of COG

To verify the rationality and correctness of the phase division of STS motion, we further analyzed the average momentum and COG characteristics of STS motion of 30 subjects at the

same moment. In the STS motion, the average COG trajectory of the subjects in the sagittal plane is shown in Figure 5, and the momentum curve in X and Z directions is shown in Figure 6.

Phase 1: Began with initiation of the motion and ended just before the hip lift-off the chair surface (18% T). There is no obvious motion in other parts of the body at this phase. The COG of the human body moves forward 51.41 mm in the horizontal direction and almost no displacement in the vertical direction (Fig. 5). The forward momentum of human body gradually increases to 13.11 N·s; the ascending momentum is almost zero (Fig. 6)

Phase 2: Began with the hip lift-off the chair surface (18% T) and ended just before the lower leg stop forward flexion and ankle joint reach the maximum dorsiflexion (40% T). The whole body moves forward and upward with the ankle as the center. The COG of human body moves forward 109.35 mm horizontally and rises 74.21 mm vertically (Fig. 5). The forward momentum of human body first increased to 21.57 N·s (32% T), then decreased to 19.38 N·s, the upward momentum increased sharply to 17.40 N·s (Fig. 6). It shows that after 32% T, the horizontal momentum of human body gradually begins to transfer to upward momentum. At this phase, because the hip leaves the chair surface, the weight of the human body concentrates on the feet, and the knee joints bear a great load, so it is very difficult to complete the motion of leaving the chair surface.

Phase 3: Began with the maximum dorsiflexion of ankle joint (40% T) and ended just before the lower leg no longer backward (91%T). The COG of human body moves forward 40.44 mm in horizontal direction and 168.85 mm in vertical direction (Fig. 5). After the forward momentum of human body decreased to 3.01 N·s (75% T), it basically did not change, the upward momentum continued to increase sharply to 31.96 N·s (56% T), and then decreased to 1.16 N·s (Fig. 6). At the end of the third phase, the human body begins to stabilize.

Phase 4: Began with the lower leg is no longer flexion backward (91% T), the COG of the human body sways slightly (Fig. 4). Body momentum tends to zero (Fig. 6), and this phase ends at the end of the STS motion.

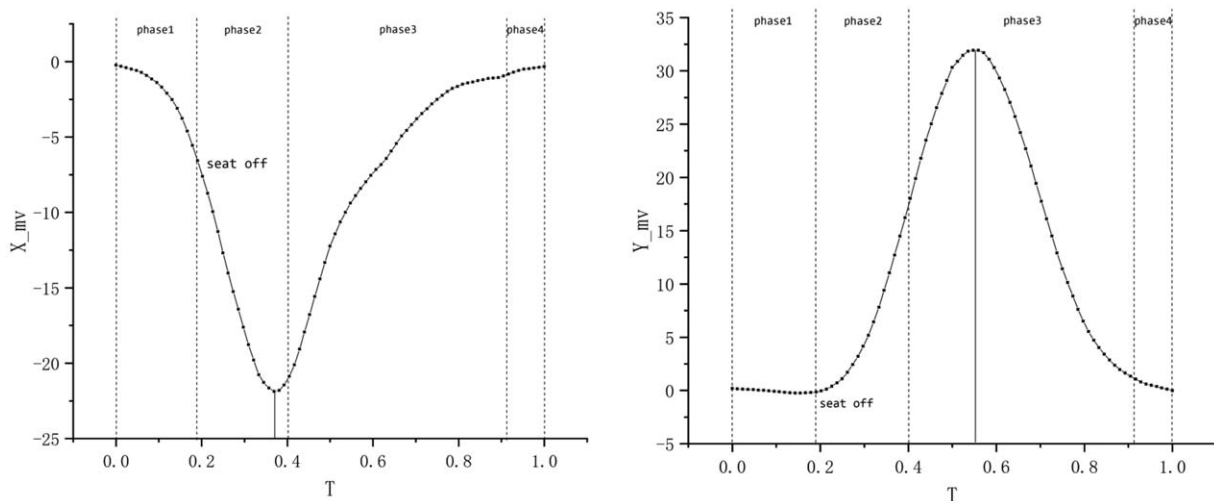


Figure 6. Momentum curve in X and Z direction (left X, right Z).

### 3.3. Transition period

According to the experimental data, we obtained the  $T_1 = 18\%T$ ,  $T_2 = 40\%T$ ,  $T^* = 44\%T$ ,  $T_3 = 91\%T$ . Here, we define the difference between  $T^*$  and  $T_2$  as the transition period. The characteristic of the transition period is that the trunk stopped flexing forward and the maximum dorsiflexion of ankle did not appear at the same moment. As shown in Figure 6, at 38% T, the momentum direction in X direction changes, less than  $T_2$  (40% T), which means the change of COG momentum direction is before the maximum dorsiflexion of lower leg, this leads to a transition period.

The division of momentum during STS shows the division of motion phases in a quantitative form, and reflects the correctness and necessity of phase division. To further analyze the reasons for the differences, the correlation analysis of body characteristic parameters and time consumption of each phase will be carried out in the following section.

### 3.4. Correlation calculation

The correlation between human body parameters and motion parameters is obtained, as shown in Table 3.

## 4. Discussion

### 4.1. Effect of transition period on STS

The existence of transition period results in the difference of STS motion among different individuals; this phenomenon may be to reduce the excessive kinetic energy generated in the initial and balance phase, which also makes the whole STS motion process smoother. Notably, 6 among the 30 subjects had longer transition periods ( $>10\%T$ ), whereas 4 subjects had a larger negative transition period ( $>10\%T$ ). For the 6 subjects with the longer transition period, their averaged trunk length is 31 mm longer than that of the other 24 subjects. Since most of the body's weight is concentrated in the trunk, therefore, the trunk flexion plays an important role in the STS. In this study, 30 subjects presented different positive and negative transition periods, which may be caused by the adjustment of COG made by different subjects. The six subjects whose transition period was more than  $+10\%T$ , it was likely due to the heavier weight of the trunk, which will cause the lag of trunk backward flexion, this may be because to complete the STS, the COG must travel a longer distance in the negative X direction. On the contrary, for the negative transition period, the COG travels a shorter distance in the negative X direction; thus, STS motion enters the third

phase earlier. This phenomenon is also closely related to individual muscle strength, but from the perspective of kinematics, this may explain the existence and difference of transition period.

### 4.2. Correlation analysis

Table 3 shows lower leg length (especially thigh length) and Dare positively correlated. Thus, people with longer lower leg should choose longer D, meaning that the length of lower leg should be used as a criterion for recommending STS trajectories for different users. As the value of D increases, people will require a longer horizontal distance to move during the balancing phase; therefore, both mechanical work and T will increase.

It is noteworthy that D is positively correlated with  $T^*$ , but not so with  $T_2$  ( $P = .15 > .05$ ). The difference between  $T^*$  and  $T_2$  represents the transition period; thus, the transition period represents the time needed to overcome the influence of a larger D. From an objective point of view, the larger D increases the time consumption of the transition period, which also proves that the reason for the long transition period is the increasing of motion time consumption caused by the body's need to guide the COG travelling a longer distance.

We found that D,  $L_1$ ,  $L_2$ , and the length of the transition period are the main factors affecting STS motion. For better design and control of SADs, we will focus on the design and control of SADs based on the law of STS motion and we will further discuss the support mode of assisted standing and the time-consuming of STS motion.

### 4.3. Body support mode for SAD

Among the 3 assistive standing support modes, that is, arm support, knee-waist support, and knee-arm-waist support, adding more arm strength greatly reduces the load on the trunk.<sup>[32]</sup> From the point of view of rehabilitation training, because the muscles of the leg, pelvis, and abdomen must exert force simultaneously during STS motion,<sup>[33,34]</sup> too much body support may result in insufficient exercise in the lower extremities, weakness of the lower limb muscles, and poor coordination during standing. Thus, it is very important to provide a reasonable level of body support. Here, we have paid special attention to the lower leg swing, where we found that the posture of the lower leg changes three times during STS motion, and the changes of the lower leg posture affect the motion of other parts of the body. Many SADs use lower leg support to assist in standing; this limits the degree of freedom of the lower leg, resulting in wrong STS trajectory of the body and uncoordinated limb motions. At the same time, the shoulder and elbow support will also have a large load on the shoulder joint, which are not beneficial for the rehabilitation of patients. Therefore, when designing SAD, we suggest that the degree of freedom of the lower leg not be limited, which will improve the coordination of the whole body. Relatively speaking, considering the influence of transition period on STS motion, the hip support combined with trunk motion guidance is recommended in this articles.

### 4.4. Assistive standing time of SAD

The body condition of people with dyskinesia may affect the length of time of STS motion. For example, children with cerebral palsy need more time to complete the STS motion compared to

**Table 3**  
The correlation coefficients (R) between pairs of variables during STS motion.

	D	$\epsilon_2$	$\epsilon_3$
$T^*$	0.42*	-0.8**	-0.7**
$L_1$	0.04*	-0.51**	•
$L_2$	0.51**	•	•
$\epsilon_2$	-0.47**	•	•
$\epsilon_3$	-0.59**	•	•
T	0.48**	•	•

\*  $P < .05$ .

\*\*  $P < .01$ .

$\epsilon_2$  and  $\epsilon_3$  = values of angle between thigh, trunk and horizontal plane at 60% T, • = variables are not correlated, STS = sit-to-stand.

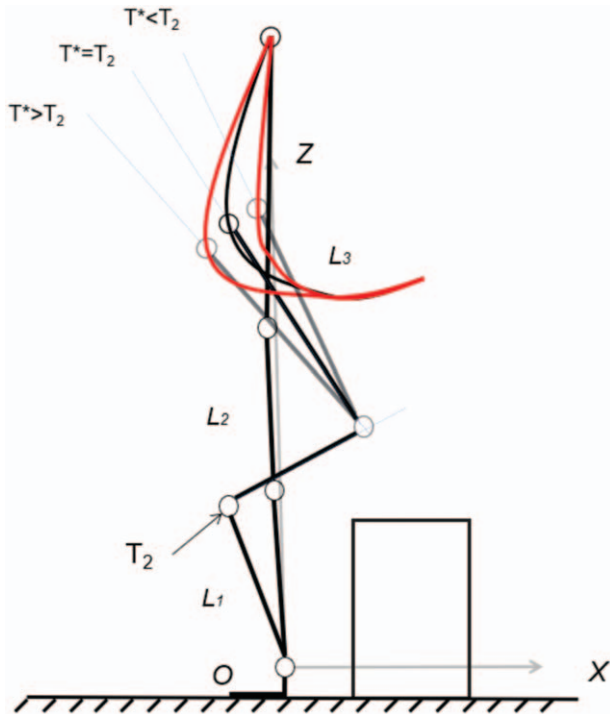


Figure 7. Schematic diagram of transition period.

lengthen the force generation time for the biceps femoris and other muscles during the balancing and rising phases, resulting in fatigue. However, if the speed is too fast, then the load will become excessive for the body of a dyskinetic person. In this study, the average STS motion time of 30 healthy subjects was 1.60 seconds. For people with dyskinesia, the assistive standing time of SADs should be changed accordingly, based also on their age and rehabilitation phase. Here, we propose that the total STS motion time of SADs should not be <1.6 seconds, and should not be >5 seconds.

Our results suggest that the longer the transition period, the larger the negative X direction displacement of the Mark1, resulting in a greater trunk flexion. However, the reverse situation will occur if the transition period is negative ( $T^* < T_2$ ), the trunk tends to enter the upright posture earlier, as shown in Figure 7. Notably, the same subjects had different transition period lengths during each STS motion; therefore, the Mark1 trajectory of the STS motion is difficult to control. The significance of the transition period is to adjust the position of the COG in the X direction. How to further control the transition period will become the key research content of individualized precision rehabilitation training. In the process of standardized STS rehabilitation training, a more sensible choice is to choose the best D and control the transition period to zero or appropriately increase the transition period. The increase of the transition period will bring a smoother trunk motion trajectory, which is beneficial to the STS motion training.

normal children.<sup>[35]</sup> Moreover, the time it takes for a SAD to complete the standing motion also affects user experience. For people with dyskinesia, STS motion is more comfortable when it is completed within 2 seconds, and becomes very difficult when it takes 5 seconds.<sup>[36]</sup> When using a SAD, a slow motion will

#### 4.5. Schematic design and control algorithm of SAD

Through the STS motion experiment, the joint point trajectory, motion time, and motion posture were obtained, and the joint velocity, acceleration, angle, angular velocity, angular acceleration, trajectory of COG, velocity of COG, and momentum were calculated, and the STS movement phases were divided, which

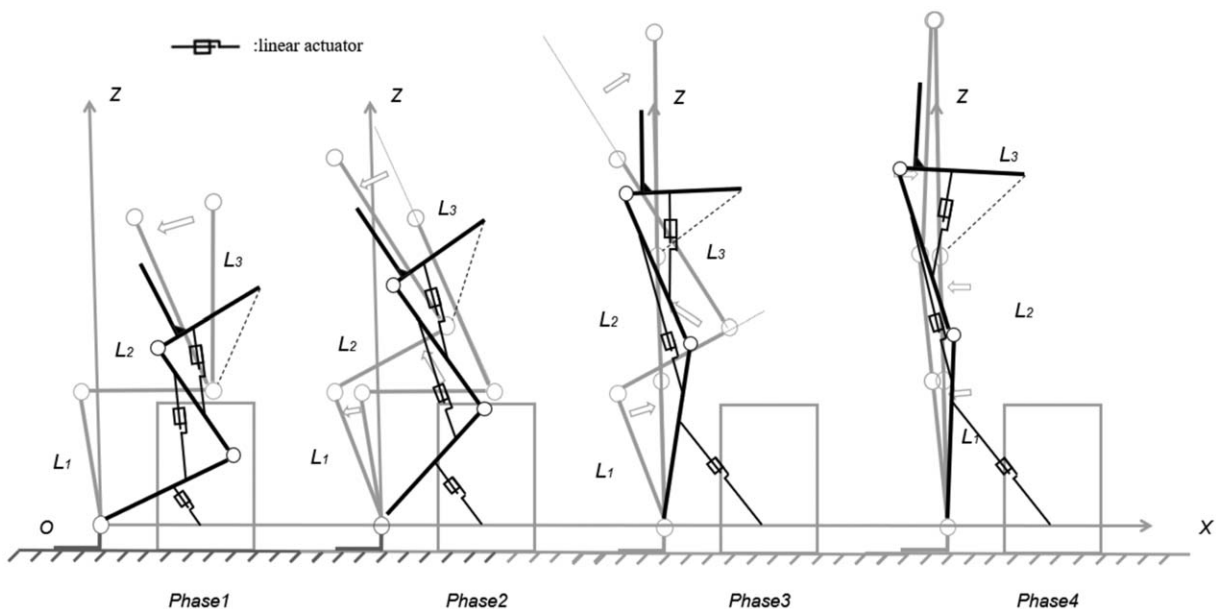


Figure 8. Schematic diagram of mechanism.



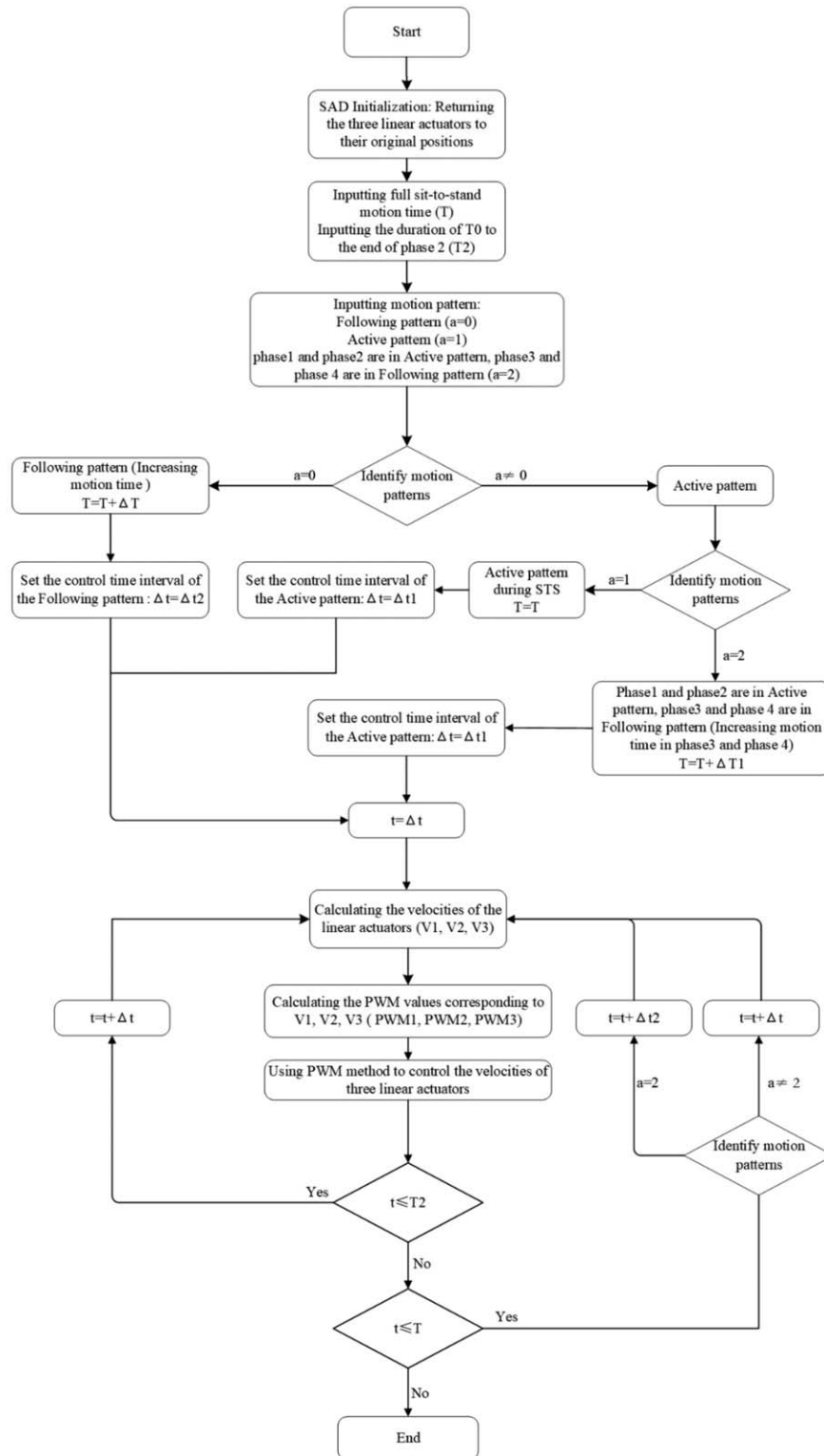


Figure 9. Flowchart of sit-to-stand assistive devices control algorithm.

provided a starting point and bases for future design and control of SAD. In this article, we have taken a 3-degree-of-freedom SAD as an example to explain the design and control of SAD.

The schematic design of the SAD is as follows:

1. Measuring the subject's weight and human dimensions, and performing STS movement experiment.
2. Measuring the positions of the marked points, drawing the human body motion trajectory, and measuring the human body STS movement duration.
3. Calculating the velocity, acceleration, angle, angular velocity, and angular acceleration of the joints, calculating the position of the center of gravity, the velocity of center of gravity, and momentum.
4. Dividing the STS movement phases according to the measured and calculated kinematics data, and determining the movement duration and movement postures of different phases.
5. Establishing a link-segment model of the human body with the ankle joint as the origin, including the shank, thigh, and trunk, and connecting the segments by pin joints.
6. According to the established link-segment model of the human body and motion trajectory obtained from the experiment, a 3-degree-of-freedom STS motion mechanism is proposed to simulate the motion of the hip joint and the posture of trunk. The mechanism is driven by three linear actuators (Fig. 8).
7. Determining the design space of the mechanism according to the human dimensions.
8. Performing forward kinematics analysis on the 3-degree-of-freedom STS motion mechanism to determine the size parameters of the mechanism.
9. Performing inverse kinematics analysis on the 3-degree-of-freedom STS motion mechanism, substituting the human motion trajectory obtained in the experiment into the mechanism kinematics expression, calculating the position data of the 3 linear actuators inversely for the subsequent motion control.
10. According to the determined movement postures of different phases, selecting the appropriate support pattern and support position, and carrying out the structure design of SAD.
11. The SAD we designed used 2 control patterns, one is the Active pattern, that is, the device drives the patient to move, and the other is the Following pattern, that is, the device follows the patient's movement. Flowchart of SAD control algorithm is as follows: (Fig. 9).

#### 4.6. Limitation

There are limitations of this work because of the subject pool and experimental protocol. First, because of focusing on young and healthy people, researchers and clinicians cannot immediately extend these results to elderly or clinical populations. Secondly, the research protocol has deviated from everyday STS motions by restricting the motion of arms. Further research is required to quantify how this normative description changes when determinants of the STS motion, such as use of handrail, increased age, constraints on speed, or chair height, are changed. Thirdly, due to the limited range of subjects available, the subjects of this article are adult male; no female subjects were selected. How to choose a support mode suitable for both male and female is the focus of

our future research. Fourthly, obesity is becoming more common in the world. However, due to the limitations of subject selection, we did not choose subjects with a high BMI. According to the literature,<sup>[37]</sup> high body mass has a great influence on STS motion. It may cause an overload on joints. In the future research, we should add subjects with high BMI to study the influence of BMI on STS motion. Finally, the knowledge of the patterns of the forces is necessary for an understanding of the cause of STS motion; such information is very useful to the researchers and clinicians. Joint moment is also an important design parameter for assistive devices. In the future research, we should carry out kinetic analysis of STS.

## 5. Conclusions

This article provides a method to divide the motion phase of STS and verify its rationality. Through the above analysis, the main factors determining the differences in STS motion among individuals are  $D$ ,  $L_1$ ,  $L_2$ , and the length of the transition period. The following factors should be considered in the design and control of SADs: we should pay attention to the whole-body posture control in STS motion, such as the posture guidance of trunk and lower leg, and could carry out specific training for different phases. SADs should provide the same  $D$  for different individuals during the STS motion. Transition period should be properly controlled, and the degree of freedom of the lower leg should not be limited.

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