

# Low-cost toilet-based sit-to-stand device for elderly with lower limb weakness

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## Abstract

Falls in the bathroom pose a serious risk to older adults, leading to physical and psychological consequences and a reduced quality of life, including fractures, head injuries, fear of movement, and loss of independence. These falls result from both personal factors, such as muscle weakness, impaired balance, chronic conditions, and medication side effects, and environmental factors, including slippery floors, inadequate lighting, insufficient assistive devices, and unsuitable sanitary fixtures. This research aimed to design and develop a low-cost toilet-based sit to stand device for elderly with lower limb weakness that can be used with both standard and multipurpose toilet bowls. The device supports safe and comfortable transitions between sitting and standing and is designed based on biomechanical principles of the sit-to-stand movement. The system comprises a mechanical unit with a linear electric actuator, an electrical control system, a C-based control program, and a battery-powered energy source. Biomedical engineering tests confirmed correct operation and stable performance of the control and safety systems. Biomedical tests confirmed stable control and safety performance. The device safely supported loads of 10-120 kg. Lifting time ranged from 11.73-16.15 s, while lowering time ranged from 11.14-12.93 s. In 30 volunteers (15 males, 15 females), knee flexion angles decreased after device use from 86.07-89.93° to 60.70-72.90° in males and from 78.10-88.13° to 59.10-67.90° in females, indicating reduced knee joint load during sit-to-stand. These results indicate that the device effectively reduces biomechanical load on the knee joint during the sit-to-stand movement.

**Keywords:** Bathroom safety, Elderly, Fall prevention, Sit-to-stand assistive device

## 1. Introduction

Thailand and many countries around the world are rapidly entering an aging society, resulting in increasing attention to the health, safety, and quality of life of older adults. One of the most common and critical problems is falls, which are a leading cause of injury, disability, and unintentional death among the elderly. Falls also have long-term psychological impacts, such as fear of recurrent falls, reduced physical activity, and loss of independence in activities of daily living [1-2]. Standing up from a seated position is a fundamental activity that older adults must perform repeatedly each day and is one of the tasks that requires substantial lower-limb muscle strength, balance, and postural control. Biomechanical studies have shown that older adults exhibit altered sit-to-stand movement patterns compared with younger individuals, such as increased reliance on the arms and greater instability of the body's center of mass, these factors increase the risk of balance loss and falls [3]. Bathrooms are among the highest-risk areas for falls within residential environments due to slippery surfaces, limited space, and the need to transition from sitting to standing, particularly when rising from a toilet. Research has indicated that adjusting seat height and providing grab bars can improve stability and reduce excessive muscle activation in older adults [4]. However, in real-world use, a substantial number of accidents during sit-to-stand movements in bathrooms continue to occur, despite the availability of assistive devices and grab bars. Several limitations remain, including incompatibility with various toilet designs,

lack of flexibility to accommodate individual body dimensions, and poor suitability for the spatial constraints of actual bathrooms. In addition, some devices are costly or require complex installation procedures, limiting accessibility for many older adults [5]. Shamim et al. conducted a biomechanical study to support the design of standing-assist devices and found that increasing seat height reduces the muscular effort required during standing, while the installation of grab bars enhances stability and postural control. Their findings highlight seat height and grab bars as critical elements in the design of standing-assist devices for older adults to improve safety and usability [6]. Hsieh et al designed a toilet standing-assist chair using a four-bar linkage mechanism to increase the seat rotation angle to more than 45 degrees, thereby improving standing efficiency while reducing system torque and driving force. The prototype was capable of supporting loads of up to 150 kg and required less driving force than commercially available devices [7]. Li Yuan et al analyzed sit-to-stand movements using inertial measurement units (IMUs) to develop a standing-assist device. The results demonstrated that designs capable of effectively supporting loads and maintaining the balance of the center of force improved stability, safety, and comfort during standing, with most users reporting high satisfaction. Based on these limitations and findings, this research aims to develop a low-cost smart sit-to-stand assistive device for older adults with lower limb muscle weakness. The device is designed to be compatible with both standard and multifunctional toilet systems and to provide

stability, structural strength, and safe load-bearing capacity for users weighing up to 100 kg. The assistive device is equipped with a movable seat platform that can automatically move vertically and forward–backward to reduce the physical effort required during standing up and sitting down. Safety is enhanced through the integration of motion limiters to restrict the range of movement. In addition, the system incorporates a user detection mechanism, an automatic seat return function that restores the seat to its lowest position when no user is detected, audible alerts during operation, and an emergency stop button to immediately halt operation and notify caregivers. The device primarily operates on battery power to enhance safety during use in bathroom environments. The developed sit-to-stand assistive device demonstrates potential to reduce the risk of falls, improve user safety, and promote independence in daily living activities among older adults, thereby contributing to long-term improvements in quality of life [8].

## 2. Materials and methods

The design of this device integrates multidisciplinary knowledge. Biomechanics is applied to analyze sit-to-stand movements, while mechanical engineering is used to design the structure and lifting mechanism, with a linear actuator as the primary driving component. An embedded control system based on a microcontroller is employed to manage system operations, in conjunction with power electronics and a DC power supply to ensure stable performance. The device is equipped with sensors to detect the upper and lower positions of the toilet seat platform. It also includes user control buttons to stop the movement at a position suitable for individual anthropometric differences. A voice-based alert system provides spoken notifications during operation. For safety, the system incorporates an emergency stop button and an external audio-visual alert system to notify caregivers outside the bathroom. The control software is developed in the C programming language to ensure accurate, stable, and reliable system operation.

### 2.1 Analyze sit-to-stand movement

The transition from a seated to a standing position is a fundamental movement in daily living; however, it is biomechanically complex because it requires coordinated interaction among the skeletal system, muscular activation, and postural control. This movement can be described as a percentage of the total sit-to-stand cycle (100%), as follows. At the initial phase (0%), the body remains in a seated position, with the center of mass (COM) located low and posterior to the base of support (BOS), while muscle activation is minimal. During the preparatory phase (~10%), the trunk flexes forward to shift the COM closer to the posterior boundary of the BOS, which helps reduce the mechanical load on the knee and hip joints. The weight transfer phase (~27%) is a critical stage in which the COM moves over the feet. During this phase, the hip, knee, and ankle extensor muscles must work synergistically to generate sufficient force. Subsequently, during the rising phase (~35%), the body continues to elevate using the strength of the lower limb muscles. At the point of maximum velocity (~45%), precise neuromuscular control is required to regulate force and movement speed in order to prevent loss of balance. Finally, in the stabilization phase (~73%), the body reaches an upright standing posture, and muscle activity decreases to maintain postural stability. In older adults experiencing age-related muscle atrophy, both muscle strength and balance control are

diminished, particularly during the weight transfer and rising phases, which are associated with a high risk of falls. This risk is further increased during sit-to-stand movements performed on toilet seats, where space is limited and floor surfaces may be slippery. Therefore, the use of sit-to-stand assistive devices designed based on biomechanical principles, such as safely facilitating COM displacement, increasing the base of support, and reducing joint loading at the knee and hip, plays a crucial role in enhancing safety, stability, and overall quality of life for older adults during daily activities [9–11].

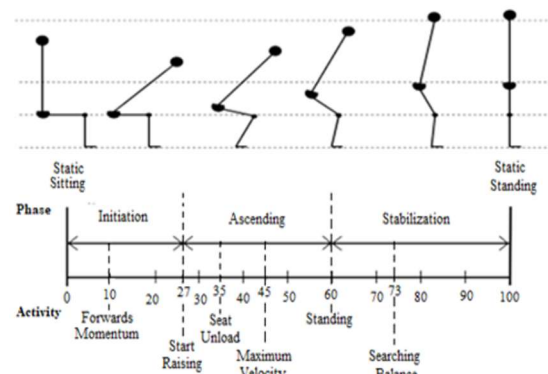


**Figure 1** Biomechanical analysis of the sit-to-stand movement (Campos Padilla, I. Y, 2015)

### 2.2 Structure and Operating Mechanism

The mechanical system was designed to safely and reliably support the body weight and movements of older adults. The main structure is fabricated from steel, stainless steel, and corrosion-resistant plastic materials, providing sufficient mechanical strength, resistance to moisture, and suitability for use in bathroom environments. The device consists of three main components: (1) the supporting base structure, (2) the seating platform, and (3) the actuator assembly. The actuator assembly generates the driving force required to control the elevation and lowering of the seating platform by partially transferring the user's body weight to the mechanical structure. As a result, muscular effort is reduced during transitions from sitting to standing and from standing to sitting. The device was designed for versatile use and can be installed in conjunction with a household toilet without requiring modification of the existing structure. The minimum height of the steel frame supporting the seating platform was set at 41 cm, approximately 1 cm higher than a standard toilet seat, while the maximum height was 56 cm. This vertical displacement range was designed to encompass the complete sit-to-stand sequence, from the initial seated posture to the pre-upright stabilization phase, consistent with biomechanical analyses of sit-to-stand movement in older adults (Figure 1). Given sex-related differences and inter-individual variability in lower limb anthropometry, particularly in thigh and shank lengths, the adjustable range was incorporated to ensure appropriate knee and hip joint angles at the initial seated position. This facilitates more favorable joint moment distribution and reduces the mechanical demand on the knee extensors during the sit-to-stand transition. Consequently, the design accommodates a wide range of user body dimensions rather than relying on mean anthropometric values alone. Furthermore, because the optimal initial seat height varies among individuals, the device was equipped with an electronic control circuit and push-button

interface. This allows users to adjust and stop the actuator-driven seating platform at a preferred height within the predefined range of motion, thereby enhancing usability and adaptability to individual needs.

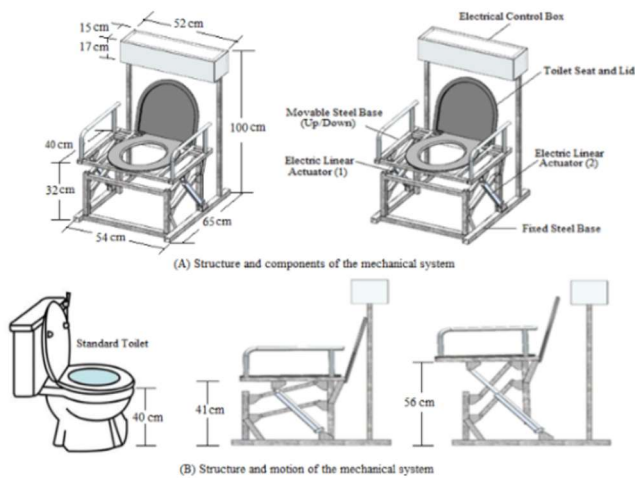


**Figure 2** Structure and range of motion of the device

### 2.3 Hardware System

Figure 3 illustrates the hardware architecture of the stand-assist device designed to support elderly users during toilet use. The system consists of three main subsystems: (1) the electrical control system, which processes input signals and generates control commands to operate the mechanical system in lifting, lowering, or stop modes. This subsystem also integrates a voice alert circuit to indicate the operational status of the seat platform to the user; (2) the mechanical system, which comprises a load-bearing structure and electric linear actuator-based motion mechanisms that support the user's body weight and transfer forces to the device structure during the lifting and lowering processes; and (3) the direct current (DC) power supply system, which provides stable and continuous DC electrical power to both the electrical control system and the mechanical system to ensure reliable operation of the device.

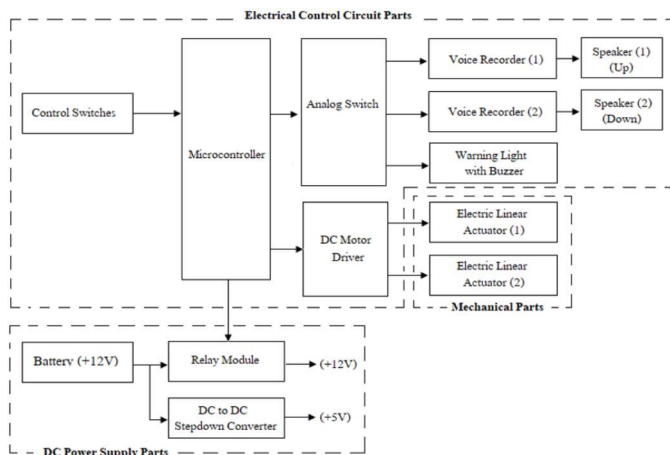


**Figure 3** Block diagram of the hardware control system of the device

The operation of the electrical control circuit of the device (Figure 4) begins with four control switches (SW1–SW4), each connected in series with a 1 kΩ resistor and interfaced with the input ports of the microcontroller (A0–A3). These switches are used to receive command signals for lifting, lowering, stopping,

and emergency shutdown. When a switch is pressed, the microcontroller processes the input signal and sends control commands to the mechanical system through a DC motor driver (MCT-HB-40A), which supplies +12 V to the electric linear actuators. As a result, the seat platform moves upward or downward according to the specified direction or stops immediately in response to the received command. During the lifting and lowering of the seat platform, the system operates in conjunction with a voice alert circuit consisting of two ISD1820 voice recording modules, which are controlled via an analog switch (CD4066BE). The system plays pre-recorded voice messages through speakers while the seat platform is moving upward or downward in order to inform elderly users of the current operating status of the device. In emergency situations, activation of switch SW4 triggers a warning light and an audible alarm module (SLAS-1101J, +12V) and immediately halts the operation of the entire system. Normal operation can resume only after the issue has been resolved and the system has been reset. In addition, a proximity sensor (JSN-SR04T) is employed to detect the presence of a user. If no user is detected in the bathroom for a period of 2 minutes, the system automatically commands the seat platform to return to its initial lowered position in cases where the seat has been left in the raised position after use. The power supply of the system is provided by a sealed lead-acid battery rated at +12 V and 9 Ah, which supplies +12 V to the mechanical system. A voltage regulator (LM2596) is used to step down and regulate the voltage to a stable +5 V for the electrical control circuit. In addition, a relay module is utilized to control the delivery of +12 V power to the actuators based on control signals from the microcontroller, ensuring that the system operates according to the predefined control logic in a stable and reliable manner.

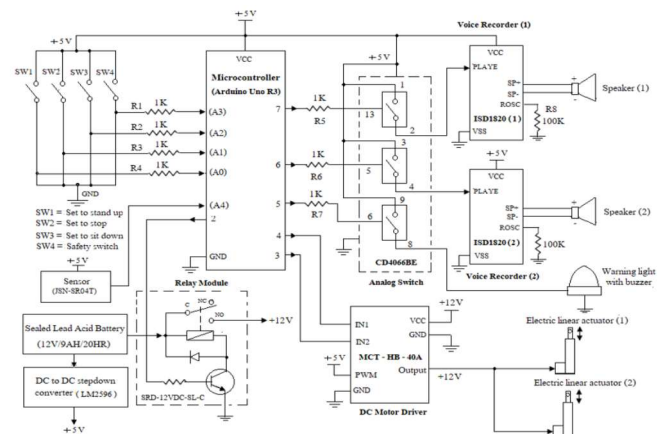


**Figure 4** Illustrates the electrical control circuit of the device

### 2.4 Software System

The control software of the device was developed using the C programming language and operates according to the flowchart illustrated in Figure 5. When the system is powered on, all required libraries are initialized and the relevant variables are configured. Subsequently, the movable steel base and seat plate, which are mechanically coupled to the lifting mechanism, are set to their initial position at the lowest level. After system initialization, the software continuously monitors the status of the control switches (SW1–SW4) and executes control actions based on the conditions of each switch, as described below. SW1 (Upward movement): When SW1 is activated, the system

generates a voice alert stating “The device is lifting the seat upward (Up)” to inform the user that the lifting process has started. Simultaneously, linear electric actuators (1) and (2) are driven in the upward direction, causing the steel base and seat plate to move upward until the predefined maximum height is reached, provided that SW2 is not pressed during operation. SW2 (Stop): When SW2 is activated, the control system immediately stops the operation of linear electric actuators (1) and (2), resulting in a complete halt of the movement of the steel base and seat plate. SW2 is intended to stop the system at a position that is appropriate for the user to stand up from the toilet safely. SW3 (Downward movement): When SW3 is activated, the system generates a voice alert stating “The device is lowering the seat downward (Down)” to notify the user that the lowering process has begun. Linear electric actuators (1) and (2) are then driven in the downward direction, allowing the steel base and seat plate to descend to the predefined lowest position, provided that SW2 is not pressed during operation and SW4 (Emergency / assistance mode): When SW4 is activated, the system enters an emergency or assistance request mode. Both visual and audible alarms, including warning lights and a buzzer, are immediately triggered. At the same time, linear electric actuators (1) and (2) are abruptly stopped to ensure user safety. The system remains in the emergency state and does not return to normal operation until the emergency condition has been properly resolved. Furthermore, the upper and lower positional limits of the toilet seat base were defined using limit switches as a control mechanism. These switches were directly integrated into the electrical control circuit to interrupt or enable actuator operation when the seat base reached predefined positions. This configuration enhances positional accuracy, prevents overtravel, and reduces the risk of structural or component damage. Importantly, the limit switch mechanism was designed to operate independently of the software control process, without interfering with or influencing the behavior of the primary control system. This functional separation allows a clear distinction between the mechanical safety system and the motion control system, thereby improving overall system stability, safety, and engineering reliability.

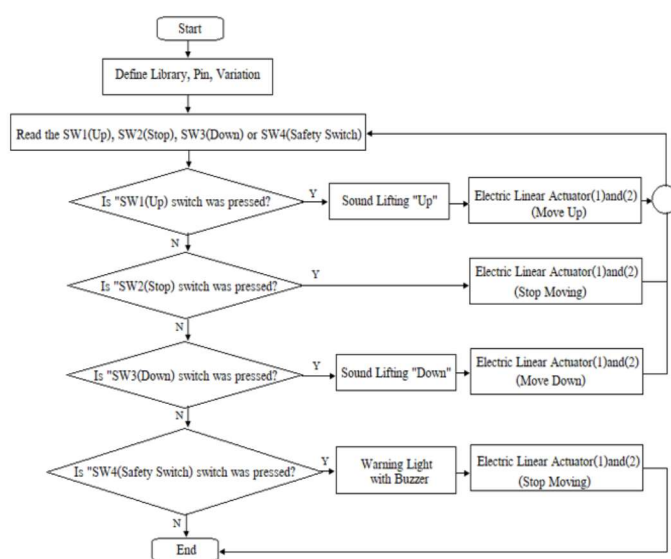


**Figure 5** Flowchart illustrating the primary operating sequence of the device.

## 2.5 Device assembly

The assembly of the standing-assist device for use with a toilet, which can be installed on both standard and multifunctional toilets, involves the integration of the mechanical system, hardware system, and software system into a complete device, as illustrated in Figure 6. The coordinated operation of all subsystems begins when the user presses a control switch. The command signal is transmitted to the microcontroller, after which the control software processes the input and sends control signals to the hardware system to drive the actuators in the mechanical system. As a result, the seat platform moves upward or downward according to the predefined operating conditions. In addition, the system is equipped with both audible and visual alert mechanisms to enhance user safety.

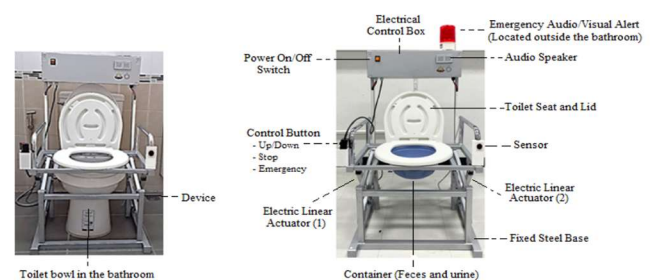


**Figure 6** Shows the device is designed and built completely.

## 2.6 Testing Procedure

This study aimed to evaluate and verify the safety and mechanical performance of the developed low-cost sit-to-stand assistive device prior to testing with elderly individuals with lower limb weakness. The testing procedures were conducted in accordance with biomedical engineering standards and were divided into two levels, as described below.

### 2.6.1 Engineering Testing

The objective of the engineering testing was to confirm the safety of the device for practical use, ensuring that it does not pose any risk to test subjects. In addition, this phase aimed to evaluate the performance of the device in terms of mechanical functionality and control system operation. These tests were conducted to ensure that the device operates correctly, exhibits sufficient stability, and performs as intended according to the design specifications before proceeding to testing with human volunteers.

#### 2.6.1.1 Functional Testing and Results

This section focused on testing the cause-and effect relationship between input signals such as commands issued via control switches or signals received from sensors and the output signals transmitted to the actuator system. The objective was to verify whether the system could correctly execute the predefined operational sequences and conditions as designed. The functional testing included evaluation of the power on-off switch operation, control switch functionality, vertical movement of the toilet seat platform, and the operation of the alert system. The results of the functional testing are presented in Table 1.

The test results presented in Table 1 indicate that both the power switch and the system control switches responded correctly and consistently to user commands. The system was able to initiate and terminate operation as specified by the user.

In addition, the voice-based audio alert system functioned in accordance with the movement status of the toilet seat platform. Specifically, clear and continuous alerts were provided during both the upward and downward movements of the seating platform, enabling users to remain aware of the operational status of the device at all times. These results demonstrate that the control system and alert system of the device operated in accordance with the predefined performance criteria. For safety-related functional testing, the device was evaluated with respect to three key safety functions: (1) a user absence detection system, in which the seating platform was automatically returned to its lowest position if no user was detected in the bathroom for more than 2 minutes after the platform had been raised and left unattended; (2) an emergency alert system; and (3) a movement limit protection system that prevented the

**Table 1** Functional test results of control switches and voice alerts during seat movement.

| Test No. | Power switch |     | Control switch |      |      | Voice announcement |      | Seat pad movement |      |
|----------|--------------|-----|----------------|------|------|--------------------|------|-------------------|------|
|          | On           | Off | Up             | Down | Stop | Up                 | Down | Up                | Down |
| 1        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 2        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 3        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 4        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 5        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 6        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 7        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 8        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 9        | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 10       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 11       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 12       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 13       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 14       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |
| 15       | ✓            | ✓   | ✓              | ✓    | ✓    | ✓                  | ✓    | ✓                 | ✓    |

Note: Evaluation criteria were Pass (✓) and Fail (×).

**Table 2** Functional test results of the user absence detection, emergency alert, and seat position limit systems.

| Test No. | Audio and visual alerts outside the bathroom |            | Seat position limit |             | User presence & auto seat return test (2 min) |      |
|----------|----------------------------------------------|------------|---------------------|-------------|-----------------------------------------------|------|
|          | Warning                                      | No warning | Upper limit         | Lower limit | Pass                                          | Fail |
| 1        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 2        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 3        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 4        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 5        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 6        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 7        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 8        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 9        | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 10       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 11       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 12       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 13       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 14       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |
| 15       | ✓                                            |            | ✓                   | ✓           | ✓                                             |      |

Note: Evaluation criteria were Pass (✓) and Fail (×).

seating platform from exceeding the predefined upper and lower boundaries during maximum elevation and minimum lowering. The results of these tests are presented in Table 2.

The test results presented in Table 2 indicate that the device demonstrated an appropriate level of safety readiness. Both the alert system and the position control system operated as designed. Therefore, it can be concluded that the device was suitable for subsequent testing with human volunteers.

#### 2.6.1.2 Mechanical Safety Testing and Results

This testing was conducted to verify that the developed intelligent sit-to-stand assistive device could safely support the body weight of volunteers without causing structural damage, system instability, or mechanical hazards to users. The testing focused on evaluating load-bearing capacity, structural strength, and operational stability based on measurable quantitative data. The test data were analyzed using statistical methods and are presented as mean  $\pm$  standard deviation (Mean  $\pm$  SD). The testing involved analysis of the relationship between different load levels and the time required for the seating platform to move upward to the maximum position and downward to the minimum position. Tests were performed over a weight range of 10-120 kg. (The device developed in this study is designed to support a maximum load of 100 kg; therefore, structural strength testing must be conducted under high-load conditions) with each load level repeated three times, and the results were recorded in Table 3. This testing aimed to assess the readiness and suitability of the device prior to evaluation with human volunteers.

Mean

$$\bar{x} = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$\bar{x}$  = mean

$x_i$  = the  $i$ th data value

$n$  = total number of data points

Standard Deviation: SD (Sample SD)

$$SD = \sqrt{\frac{\sum_{i=1}^n (x_i - \bar{x})^2}{n-1}} \quad (2)$$

Figure 7 illustrates the mechanical strength and structural safety testing procedure of the device using calibrated weights ranging from 10 to 120 kg placed on the toilet seat platform to simulate the body weight of volunteers under real-use conditions. During testing, a stopwatch was used to measure the lifting time, dwell time, and lowering time of the seating platform. In addition, the overall operational condition of the device was monitored to verify normal functionality prior to evaluation with human volunteers.

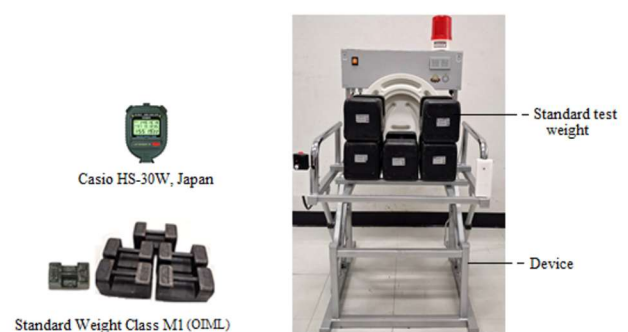


**Figure 7** Structural strength testing of the device under applied loads ranging from 10 to 120 kg.

**Table 3** Results of the mechanical safety testing of the device under different load levels.

| Weight (kg) | Lifting time (s)<br>Mean $\pm$ SD | Load holding time (5 min) | Lowering time (s)<br>Mean $\pm$ SD | Device Condition |
|-------------|-----------------------------------|---------------------------|------------------------------------|------------------|
| 10          | 11.73 $\pm$ 0.03                  | ✓                         | 11.14 $\pm$ 0.02                   | ✓                |
| 20          | 12.23 $\pm$ 0.04                  | ✓                         | 11.55 $\pm$ 0.02                   | ✓                |
| 30          | 12.41 $\pm$ 0.03                  | ✓                         | 11.99 $\pm$ 0.03                   | ✓                |
| 40          | 12.64 $\pm$ 0.02                  | ✓                         | 12.00 $\pm$ 0.06                   | ✓                |
| 50          | 12.95 $\pm$ 0.08                  | ✓                         | 12.14 $\pm$ 0.01                   | ✓                |
| 60          | 13.38 $\pm$ 0.12                  | ✓                         | 12.20 $\pm$ 0.02                   | ✓                |
| 70          | 13.90 $\pm$ 0.12                  | ✓                         | 12.20 $\pm$ 0.03                   | ✓                |
| 80          | 14.30 $\pm$ 0.13                  | ✓                         | 12.21 $\pm$ 0.02                   | ✓                |
| 90          | 14.69 $\pm$ 0.04                  | ✓                         | 12.28 $\pm$ 0.04                   | ✓                |
| 100         | 15.22 $\pm$ 0.23                  | ✓                         | 12.27 $\pm$ 0.03                   | ✓                |
| 110         | 15.56 $\pm$ 0.11                  | ✓                         | 12.34 $\pm$ 0.08                   | ✓                |
| 120         | 16.15 $\pm$ 0.28                  | ✓                         | 12.93 $\pm$ 0.23                   | ✓                |

**Note:** Pass (✓) and Fail (✗)

Based on Table 3, the results of the lifting and lowering time tests of the toilet seat base under loads ranging from 10–120 kg are presented. The results indicate that as the applied load increased, the lifting time showed a continuous upward trend, increasing from  $11.73 \pm 0.03$  s at 10 kg to  $16.15 \pm 0.28$  s at 120 kg. This demonstrates a clear relationship between the applied load and the operating time of the driving system. In contrast, the lowering time remained relatively constant across all load conditions, ranging from  $11.14 \pm 0.02$  s to  $12.93 \pm 0.23$  s, with low standard deviation values. This indicates good stability of the control system during the lowering phase, even under varying load levels. Furthermore, the load-holding test for a duration of 5 minutes showed that the device was able to maintain its position at all tested load levels without displacement or system malfunction. This reflects the reliability of both the mechanical structure and the control system. To further analyze the data, graphs illustrating the relationship between the applied load (kg) and the lifting and lowering times (s) were generated. The results of this analysis are presented in Figure 8.

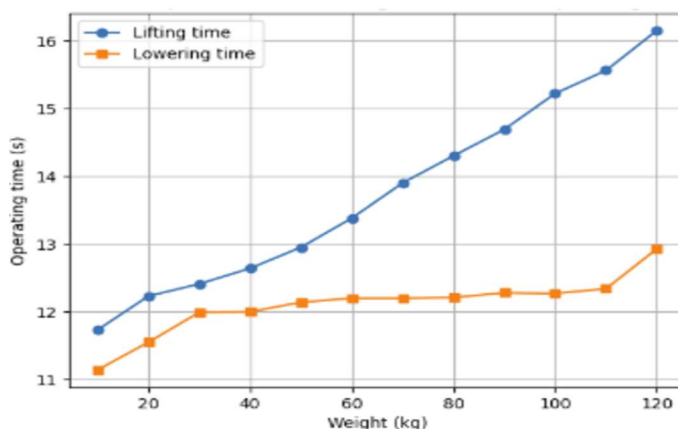


**Figure 8** Graph illustrating the relationship between the applied load (kg) and the lifting–lowering time of the seat base (s).

Based on the overall results shown in Figure 8, it can be concluded that the device operates stably and is capable of supporting increased loads as designed. The increase in lifting

time remains within predictable limits without any system abnormalities, while the lowering time remains consistent. These results indicate the effectiveness of the control system and confirm the suitability of the device for testing with human volunteers.

## 2.6.2 Human Subject Testing

The testing of the low-cost toilet-based sit-to-stand assistive device was conducted solely to evaluate the engineering performance and safety of the prototype and was not intended for medical diagnosis or treatment. Therefore, the participants were healthy individuals recruited from the general population. To ensure suitability and safety, eligible volunteers were healthy adults aged 20–60 years, of any sex, who participated voluntarily. Participants were required to be in good health and able to perform sitting and standing movements independently according to their natural movement patterns. Exclusion criteria included the presence of musculoskeletal, neurological, or cardiovascular disorders; a history of knee or hip injury or surgery within the past six months; body weight exceeding the load-bearing capacity of the device; pregnancy; or frequent episodes of dizziness or syncope. Individuals who did not meet these criteria were excluded from the study.

### 2.6.2.1 Sit-to-Stand Movement Evaluation and Results

This test aimed to measure the knee joint angle during the sit-to-stand movement, from the lowest to the highest position of the toilet seat base, excluding the standing-to-sitting phase. The test utilized the developed sit-to-stand assistive device, Kinovea motion analysis software, and a smartphone mounted on a fixed tripod for lateral video recording. Volunteer data (15 males and 15 females, including age, body weight, and height) were used as reference variables. During the experiment, volunteers sat in a standardized posture with consistent trunk and foot positions. The device was activated using a remote controller to initiate the standing motion, and the movement was recorded until standing was achieved. Each volunteer performed three trials. Knee joint angles were analyzed from the recorded videos, and the results were reported as mean  $\pm$  standard deviation (Mean  $\pm$  SD).



**Figure 9** Sequence of sit-to-stand movement during testing of the assistive device

Based on Table 4, the knee joint angle measurements of 15 male volunteers are presented. Before using the sit-to-stand assistive device, the knee joint angles ranged from  $86.07 \pm 0.76^\circ$  to  $89.93 \pm 1.25^\circ$ , which is consistent with a typical sitting posture. After using the assistive device, the knee joint angles decreased to a range of  $60.70 \pm 1.39^\circ$  to  $72.90 \pm 0.79^\circ$ , indicating greater knee extension during the movement from sitting to standing. The results show that all male volunteers exhibited a reduction in knee joint angle after using the device, demonstrating that the sit-to-stand assistive device effectively reduces knee flexion during the standing-up phase. This reduction likely decreases the muscular effort required from the lower limbs, thereby enabling volunteers to stand up more easily and with improved stability.

**Table 4** Results of knee joint angle measurements before and after using the sit-to-stand assistive device (male volunteers).

| Test No. | Age (years) | Weight (kg) | Height (cm) | Knee Angle Measured by Kinovea (°) (Mean ± SD) |              |
|----------|-------------|-------------|-------------|------------------------------------------------|--------------|
|          |             |             |             | before                                         | after        |
| 1        | 34          | 57          | 173         | 87.00 ± 1.16                                   | 63.93 ± 2.07 |
| 2        | 25          | 82          | 174         | 87.73 ± 0.85                                   | 70.23 ± 1.47 |
| 3        | 20          | 80          | 174         | 87.67 ± 0.81                                   | 71.67 ± 0.76 |
| 4        | 20          | 63          | 172         | 88.07 ± 0.29                                   | 70.30 ± 1.06 |
| 5        | 55          | 61          | 166         | 86.63 ± 0.40                                   | 66.67 ± 1.92 |
| 6        | 21          | 53          | 176         | 88.37 ± 1.56                                   | 72.90 ± 0.79 |
| 7        | 37          | 60          | 160         | 86.30 ± 2.44                                   | 60.70 ± 1.39 |
| 8        | 28          | 50          | 170         | 88.27 ± 2.69                                   | 67.20 ± 0.95 |
| 9        | 22          | 60          | 165         | 86.97 ± 0.75                                   | 61.07 ± 0.80 |
| 10       | 43          | 65          | 172         | 87.37 ± 1.92                                   | 67.23 ± 1.76 |
| 11       | 22          | 80          | 175         | 87.10 ± 1.84                                   | 66.83 ± 0.46 |
| 12       | 57          | 62          | 173         | 86.07 ± 0.76                                   | 68.40 ± 1.39 |
| 13       | 22          | 89          | 178         | 86.30 ± 1.31                                   | 70.17 ± 0.25 |
| 14       | 20          | 57          | 170         | 87.63 ± 0.85                                   | 64.73 ± 2.91 |
| 15       | 24          | 60          | 175         | 89.93 ± 1.25                                   | 68.87 ± 0.67 |

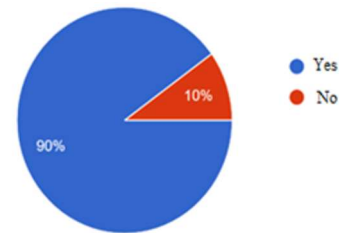
Based on Table 5, the analysis of knee joint angles in 15 female volunteers shows that before using the sit-to-stand assistive device, the knee flexion angles ranged from  $78.10 \pm 0.46^\circ$  to  $88.13 \pm 1.05^\circ$ , which corresponds to a natural sitting posture. When using the assistive device, the knee joint angles decreased to a range of  $59.10 \pm 0.79^\circ$  to  $67.90 \pm 0.87^\circ$ , indicating increased knee extension during the posture transition. This trend was consistently observed in all female volunteers, demonstrating that the developed assistive device effectively supports the movement from sitting to standing by reducing knee flexion and decreasing the muscular effort required from the lower limbs. As a result, the sit-to-stand motion became smoother and more controlled.

**Table 5** Knee joint angles before and after using the sit-to-stand assistive device (female volunteers)

| Test No. | Age (years) | Weight (kg) | Height (cm) | Knee Angle Measured by Kinovea (°) (Mean ± SD) |              |
|----------|-------------|-------------|-------------|------------------------------------------------|--------------|
|          |             |             |             | before                                         | after        |
| 1        | 21          | 57          | 160         | 85.50 ± 1.97                                   | 63.67 ± 0.90 |
| 2        | 26          | 71          | 165         | 86.57 ± 1.62                                   | 63.87 ± 2.44 |
| 3        | 41          | 58          | 158         | 88.13 ± 1.05                                   | 63.07 ± 1.25 |
| 4        | 22          | 51          | 164         | 87.83 ± 1.53                                   | 62.97 ± 0.84 |
| 5        | 38          | 65          | 160         | 88.10 ± 1.01                                   | 64.67 ± 1.63 |
| 6        | 21          | 85          | 158         | 86.20 ± 1.05                                   | 62.47 ± 1.89 |
| 7        | 41          | 41          | 159         | 87.17 ± 0.85                                   | 63.23 ± 2.05 |
| 8        | 22          | 74          | 159         | 87.20 ± 1.47                                   | 60.90 ± 1.57 |
| 9        | 47          | 62          | 167         | 86.60 ± 0.56                                   | 67.40 ± 0.26 |
| 10       | 21          | 55          | 165         | 87.07 ± 0.75                                   | 65.53 ± 1.04 |
| 11       | 52          | 57          | 163         | 87.00 ± 1.17                                   | 67.90 ± 0.87 |
| 12       | 21          | 58          | 158         | 87.37 ± 0.50                                   | 59.10 ± 0.79 |
| 13       | 22          | 45          | 154         | 87.83 ± 1.15                                   | 60.57 ± 1.16 |
| 14       | 29          | 58          | 152         | 78.10 ± 0.46                                   | 62.80 ± 2.29 |
| 15       | 22          | 73          | 167         | 87.27 ± 0.95                                   | 66.60 ± 1.00 |

### 2.6.2.2 Results of User Satisfaction Evaluation

User satisfaction after using the sit-to-stand assistive device was evaluated using a quantitative questionnaire based on a Likert scale. A total of 30 volunteers, including both male and female participants, were asked to rate their opinions regarding the device's performance, convenience, stability, safety, and design suitability. The satisfaction levels were defined on a five-point scale as follows: very high = 5, high = 4, moderate = 3, low = 2, and very low = 1. The evaluation results were analyzed and presented as percentages, as shown in Figure 10, to support the assessment of the effectiveness and suitability of the developed device.

**Figure 10** User satisfaction after using the device among 30 volunteers.

The analysis showed that 90% of the volunteers were satisfied with the use of the sit-to-stand assistive device, as it effectively facilitated the transition from sitting to standing and was perceived as convenient, stable, robust, and safe. However, 10% of the volunteers reported dissatisfaction, which may be attributed to individual differences in physical characteristics, such as height and body weight or a lack of familiarity with the device's operating mechanism, resulting in reduced ease of use during the standing-up process.

## 3. Results and discussion

This study evaluated the safety, mechanical performance, and preliminary usability of a low-cost sit-to-stand assistive device prior to testing in elderly individuals with lower limb weakness. The results from both engineering and human subject testing indicate that the device meets its design objectives and is suitable for further clinical evaluation. Engineering tests demonstrated that the control system operated reliably, with all functional components achieving a 100% pass rate. The system showed a consistent relationship between user inputs and actuator responses, while the integrated audio feedback enhanced user awareness during operation. Safety mechanisms including user absence detection, emergency alerts, and movement limit protection functioned effectively, supporting safe real-world use. Mechanical testing confirmed that the device has adequate structural strength and load-bearing capacity. Although lifting time increased with higher loads, performance remained stable and predictable, even beyond the intended maximum load. Lowering time remained relatively constant, indicating effective control during descent. The device also maintained stability under sustained loads, reflecting reliable structural and actuator performance.

## 4. Conclusions

This study aimed to design, develop, and evaluate a low-cost sit-to-stand assistive device for elderly individuals with lower limb weakness. The device was designed to be compatible with both standard and multipurpose toilet systems. Engineering-

based testing, conducted in accordance with biomedical engineering principles, was performed to assess mechanical safety, control system stability, and overall readiness prior to trials involving the target population. The results demonstrated that the control and safety systems operated reliably, with stable performance and consistent responsiveness to input commands. Mechanical safety testing under loads ranging from 10 to 120 kg confirmed that the device could safely support applied weights. Lifting time increased proportionally with load, while lowering time remained relatively constant, indicating effective coordination between the actuation and control systems. Testing with 30 healthy volunteers showed that the device significantly reduced knee flexion during the sit-to-stand movement in both male and female participants, contributing to a smoother and more stable transition. In terms of user perception, 90% of participants reported satisfaction with the device's performance and safety. The remaining 10% expressed dissatisfaction, likely due to differences in physical characteristics, such as height and body weight, as well as limited familiarity with the device, which may have affected ease of use. In conclusion, the developed device demonstrates strong potential in terms of safety, functionality, and user acceptance, supporting its future application in elderly individuals or those with lower limb weakness.

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