

Effect of different handrail types and seat heights on kinematics and plantar pressure during STS in healthy young adults

Xiaolong Han, BD, Qiang Xue, MD*, Shuo Yang, PhD, Shouwei Zhang, BD, Min Li, BD

Abstract

Handrail type and seat height both significantly influence sit-to-stand (STS) movement. However, research on the associations between handrail type, seat height, and their cumulative effect on STS kinematics and changes in plantar pressure distribution during STS under different handrail types and seat heights is insufficient.

The main objective of this study was to investigate the effect of different handrail types and seat heights on the kinematics and plantar pressure in healthy adults during STS.

The study was conducted on 26 healthy young adults. Six conditions were tested: low seat (LS) and vertical handrail; LS and horizontal handrail (HH); LS and bilateral handrail; high seat (HS) and vertical handrail; HSHH; HS and bilateral handrail. The movement time, trunk tilt angle, and time from hindfoot to forefoot peak pressure were analyzed and compared.

A significant difference was found in handrail type ($P < .001$) and seat height ($P < .02$) for the total movement time of STS. A significant difference was also found for the maximum trunk tilt angles ($P < .001$) in handrail types. There was an interaction between handrail type and seat height for the time from hindfoot to forefoot peak pressure of STS ($P = .003$).

Using HSHH could take less time to accomplish STS movement; it also reduced the maximum trunk tilt angle and thus reduce the risk of falling; the time from hindfoot to forefoot peak pressure when using HSHH was short and subjects could accomplish STS movement easier.

Abbreviations: BH = bilateral handrail, HH = horizontal handrail, HS = high seat, LS = low seat, STS = sit-to-stand, VH = vertical handrail.

Keywords: handrail type, kinematic analysis, plantar pressure, seat height, sit-to-stand

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According to the test collected STS kinematic data of 26 subjects, the differences of the total movement time, the maximum trunk tilt angles, and the time from hindfoot to forefoot peak pressure in STS movement were analyzed among 6 conditions, and kinematic laws governing STS transfer were summarized.

This paper investigated the effect of different handrail types and seat heights on kinematics and plantar pressure in healthy adults during STS, and proposed an assisted standing strategy; that is, choose to use a HSHH, which provides an important reference for the design of assistive devices, the patient care and rehabilitation therapy.

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Tianjin Key Laboratory of Integrated Design and On-line Monitoring for Light Industry & Food Machinery and Equipment, College of Mechanical Engineering, Tianjin University of Science & Technology, Tianjin, China.

* Correspondence: Qiang Xue, Tianjin University of Science & Technology, College of Mechanical Engineering, Tianjin, China (e-mail: qxue@tust.edu.cn).

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1. Introduction

Sit-to-stand (STS) movement is one of the most common activities of daily life.^[1] On average, healthy adults perform approximately 60 (± 20) STS movements every day.^[2] STS movement has a heavy burden on joints and requires a large amount of muscle strength,^[3] coordination, and accurate balance control.^[4] For people with lower limb disabilities, standing up can be particularly challenging, and the difficulty of STS movement can be reflected by changes in plantar pressure.^[5] Handrail supports allow the muscles of the legs to be assisted by the muscles of the arms and could reduce lower limb muscle load and joint torque, enabling a more stable STS movement.^[6] The change of seat height also affects lower limb joint torque and body balance during STS movement.^[7,8]

Numerous studies have investigated the effects of handrails on STS movement. O'Meara and Smith^[9] analyzed the effects of unilateral grab rail assistance during STS movement; they found that such assistance may be appropriate for individuals with asymmetric impairments, such as arthritis or stroke. In addition, unilateral grab rail could decrease the knee joint moment in the opposite side. Qiu et al^[10] investigated the effects of positioning a handrail at the side of the affected or nonaffected limb on STS movement; they found that positioning a handrail at the affected side can reduce knee burden and improve stability. Yamakawa et al^[11] conducted the same kind of study and demonstrated that a handrail on either the healthy or impaired side significantly reduces the experienced physical burden. Furthermore, the maximum knee moment was smaller when the handrail was on the impaired side than it was on the healthy side. Chihara

et al^[12] determined the optimum position and orientation of handrail for STS movement, finding that when the handrail was tilted back 38.4° and the height was 1.3 times the height of the acromion, the total physical load (formulated as the weighted sum of the EMGs) was the lowest. Kato et al^[13] designed a new curved-angled handrail and found that the reaction forces generated in the anterior posterior and upward downward directions during STS movements using the curved-angled handrail were significantly higher than those generated using a conventional vertical handrail (VH; $P < .001$). It means that curved-angled handrail provided greater assistance during STS. Sekiguchi et al^[14] investigated the effects of different types of unilateral handrails during STS, they found that the use of a shelf bar generated a larger bar reaction force in the vertical direction than a vertical grab bar and horizontal grab bar ($P < .05$); hence, shelf bar use may decrease lower limb burden during STS. Handrails are often installed in bathrooms to help the elderly stand up. Dekker et al^[6] compared the use of 3 different handrails in bathroom, they pointed out that there is a preference for VH and bilateral grab bars during STS. Kennedy et al^[15] came to the same conclusion as Dekker et al, but they noted that this preference may present an increased risk of falls when using bilateral grab bars in the bathroom. They suggested that the 2 VHs should be considered in the design of accessible bathroom, because the center of pressure deviation when using this handrail form was the smallest. Lee et al^[16] investigated the effects of bilateral grab bars on the biomechanics of STS toilet transfers, and they found that the use of such bars can help reduce the peak magnitude of moments at leg joints. However, bilateral grab bar widths and heights had few effects on the moments at leg joints. Kinoshita^[17] investigated the handrail position and shape that best facilitate STS movement, the results showed that “high and low” handrail positions best facilitate STS movement in the elderly by reducing the time required to perform STS movements and by decreasing torque and subsequent wear on the joints and muscles. Kinoshita et al^[18] also studied the effect of handrail height on STS movement, determining that using low handrails, STS movement resulted in an increased hip flexion angle, ankle dorsiflexion angle, trunk forward tilt angle, and a higher forward center-of-gravity shift than when not using handrails in young adults during seat-off ($P < .001$). In contrast, using high handrails resulted in a smaller hip flexion angle and trunk forward tilt angle in young adults. Qiu et al^[19] concentrated on the effect of handrail grip position and trunk-tilt angle differences in terms of lower-limb joint moments; they found that the participants preferred to stand up when the upper body was tilted 30°, and the handrail grip position was located beneath the chest. In addition, they found 2 types of strategies for handrail use. One is using handrail temporarily when lift off the seat, the other is using handrail during the entire STS movement. Chang et al^[20] designed an additional armrest that can be attached to a standard walker, the new additional armrests can provide larger acceleration to perform STS and enable elderly people to spend less time during STS. The above studies indicated that handrails are helpful for users during STS, and the appropriate form and position of handrail can greatly reduce lower-limb joint torque

Many studies also investigated the effect of seat height on STS movement, finding that choosing the correct seat height can make STS movements easier. Lee and Lee^[8] analyzed the effects of an elevated chair on STS tasks performed by cerebral palsy patients; the sway with STS performed from the elevated chair

was found to decrease compared to that with STS performed from a standard chair ($P < .05$). Blache et al^[7] investigated the influence of seat height and foot position in the sagittal plane on lumbar spine load and found that increasing the seat height could reduce lumbar spine load during STS. Therefore, they pointed out that standing from a high seat (HS) position may be beneficial for individuals with poor lumbar muscle strength. Kuo et al^[21] described the sagittal kinematics of the spine and lower limb in healthy older adults during STS from 2 seat heights; they reported that lumbar flexion was increased relative to hip flexion at the lower seat height ($P < .001$). Lee and Lee^[22] investigated the effects of changing angle and height of toilet seat on movements during STS and showed that increasing toilet seat height affected forward-and-backward swaying during standing up but did not affect the ground reaction force and side-to-side swaying. Ng et al^[23] investigated the interaction of seat height and arm position with completion times for the 5 times STS test in older women. They found that the significant differences were only between different seat heights rather arm positions, and higher seat height could shorten the STS movement time. Medeiros et al^[24] investigated the influence of seat height and foot placement positions on postural control in children with cerebral palsy during STS. They found that seat height had an influence on the kinematic variables during STS.

Changes in plantar pressure can also reflect the difficulty of STS movement. Sato et al^[5] analyzed differences in plantar pressure between standing from an ordinary seat and standing from a low-repulsion mat. They found that the time from hindfoot to forefoot peak was significantly shorter with the ordinary chair than with the mat ($P < .05$). Through the above study they pointed out that the time from hindfoot to forefoot peak pressure could be the best indicator of STS movement difficulty.

Based on previous studies on STS movement with different handrail types or seat heights, it was determined that handrail type and seat height both significantly influence STS movement. However, there is no research on the relationship between handrail type, seat height, and their cumulative effects on STS kinematics. Studies regarding changes in plantar pressure distribution during STS under different handrail types and seat heights are also fewer. The kinematics and plantar pressure data obtained under the comprehensive conditions of different handrail types and seat heights could provide a significant reference for understanding the kinematic characteristics, motion posture and plantar pressure changes of STS; It could make clinicians have a new sight on STS movement in condition of handrail and seat together used, so as to formulate a reasonable rehabilitation training plan; It could also provide a more comprehensive basis for the design of handrail and seat in assistive devices. Hence, the main objective of this study was to investigate the effect of different handrail types and seat heights on kinematics and plantar pressure in healthy adults during STS.

We first hypothesized that the use of different handrail types and seat heights during STS movement would influence trunk forward tilt angle. Second, we hypothesized that the use of different handrail types and seat heights would change the time-consuming proportion of each STS movement phase. Finally, we hypothesized that the time from hindfoot to forefoot peak pressure would be different under different handrail types and seat heights.

Table 1
Participant characteristics.

Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m ²)
26.9±6.7	174.3±6.6	69.1±8.9	22.7±2.8

Values are expressed as the mean±standard deviation.
BMI = body mass index.

2. Method

2.1. Participants

We recruited 26 healthy adult male subjects to perform the STS motion tests. The inclusion criteria were that the subjects could complete STS independently, and the exclusion criteria were patients with any major orthopedic surgery, neurological disease, active musculoskeletal problem, or had any sensory, visual, auditory, or cognitive impairments. The inclusion time was from April 10 to April 25, 2020. This study was approved by the Academic Ethics and Scientific Ethics Special Committee of the Academic Committee of Tianjin University of Science and Technology. All subjects signed an informed consent statement prior to participating in this study. The information of participants is provided in Table 1.

2.2. Materials

Kinematic data in the sagittal plane were collected using a high-definition camera (EOS 200D II, 1920 × 1080 pixel, Canon) with a sample rate of 60Hz. Plantar pressure was determined using flexible film pressure sensors (MD30-60, Leanstar, Suzhou, China) with a sample rate of 20Hz. Film pressure sensor is a kind of resistance sensor, the output resistance decreases with any increase in pressure applied to the sensor surface; thus, plantar pressure can be measured through a specific pressure-resistance relationship. In the process of measurement, to convert the electrical signal into the pressure value, we built a test system (Fig. 1); this figure provides the connection circuit diagram of 4 flexible film pressure sensors simultaneously measured by 4 channel MY2901s. Three handrail types and 2 seat heights were tested: low seat (LS) and HS; and VH, horizontal handrail (HH), and bilateral handrail (BH) (Fig. 2A and B). The height of the LS was the knee height referring to the vertical distance between the

ground and the lateral femoral epicondyle, and the HS corresponded to 120% of the knee height. The BH height was adjusted to the greater trochanter in the standing position; it was set at each side of the chair with a separation distance of 0.7 m. The vertical and HH heights were both adjusted to 110% of the acromion height when subjects sat on the seat; when subjects used these 2 kinds of handrails, the distance between the grasping positions was their shoulder width. Four flexible film pressure sensors were attached to the left forefoot, left hindfoot, right forefoot, and right hindfoot (Fig. 2C).

2.3. Protocol

This study is observational. Before the test, red markers were attached to the following anatomical landmarks on the right side of the subject’s body: shoulder, hip, knee, and ankle joints. Participants were asked to wear tight black clothing to reduce the likelihood of misalignment between the body, clothing, and fat wobble, all of which may affect data collection.

When conducting the test, participants chose a comfortable foot position by themselves. They were instructed to hold the handrails and stood up from a backless chair at a self-selected speed when they heard the verbal command “ready and stand up”. Pressure sensors and a camera recorded the data simultaneously. The movement ended with the subject’s self-report “stop” when they maintained an upright position and no longer swayed. STS movements were performed under the following 6 conditions (Fig. 3):

- (a) Sitting in a LS and holding onto the VH with both hands.
- (b) Sitting in a LS and holding onto the HH with both hands.
- (c) Sitting in a LS and holding onto the BH with both hands.
- (d) Sitting in a HS and holding onto the VH with both hands.
- (e) Sitting in a HS and holding onto the HH with both hands.
- (f) Sitting in a HS and holding onto the BH with both hands.

In each condition, participants were asked to practice 2 STS trials to become familiar with the process of the study. After practice trials, 3 trials of the STS task were conducted. The subjects rested for an appropriate amount of time between each trial. Subjects, researchers, and the measurement process may cause bias in the test procedure; therefore, we paid special attention to controlling these factors in the test procedure to ensure the measurement results’ accuracy and reliability. For

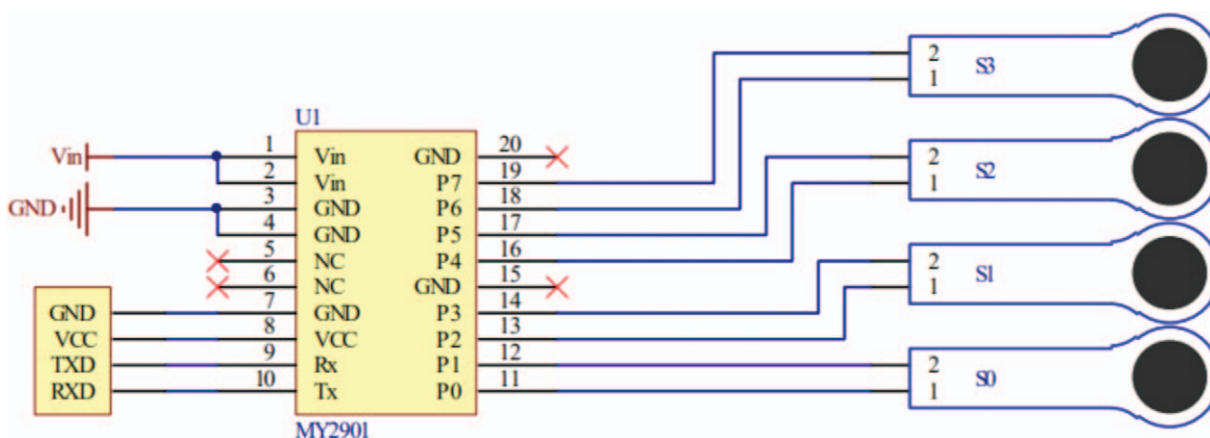


Figure 1. Connection circuit diagram for 4 pressure sensors.

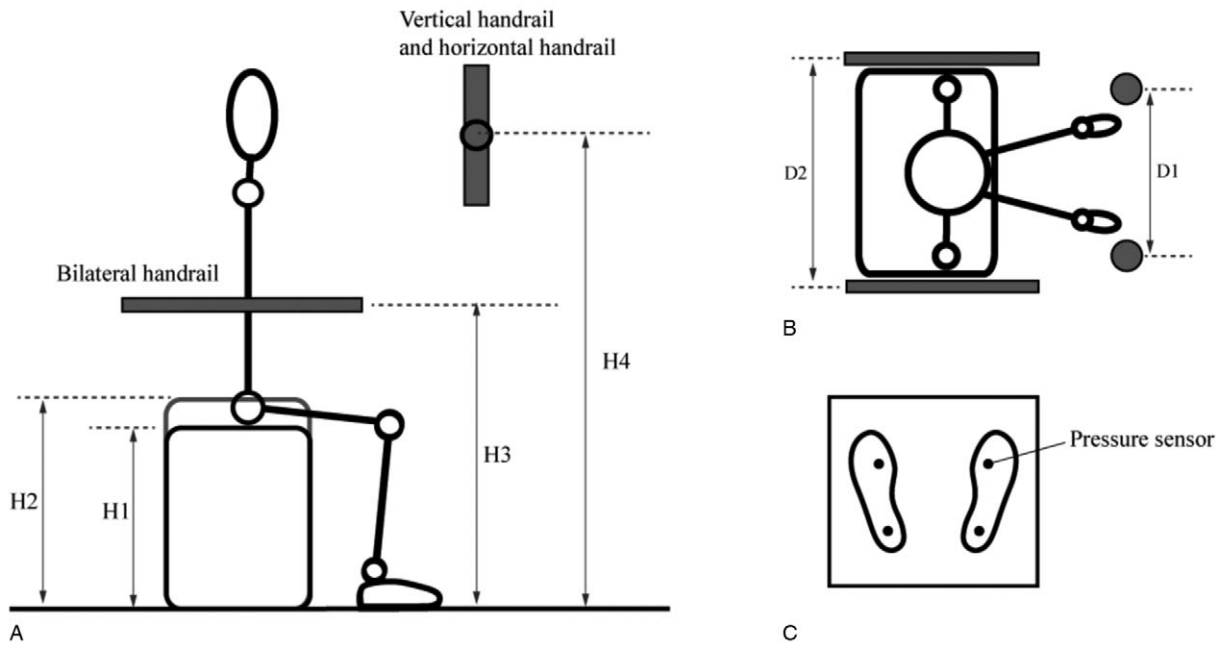


Figure 2. Test equipment. (A) Height of the low seat ($H1 = \text{knee height}$), high seat ($H2 = 120\%$ of knee height), bilateral handrail ($H3 = \text{greater trochanter in standing position}$), vertical and horizontal handrails ($H4 = 110\%$ of acromion height when subjects sat on the seat). (B) Width between vertical ($D1 = \text{shoulder width}$), horizontal ($D1 = \text{shoulder width}$), and bilateral ($D2 = 700\text{mm}$) handrails. (C) Position of 4 flexible film pressure sensors.

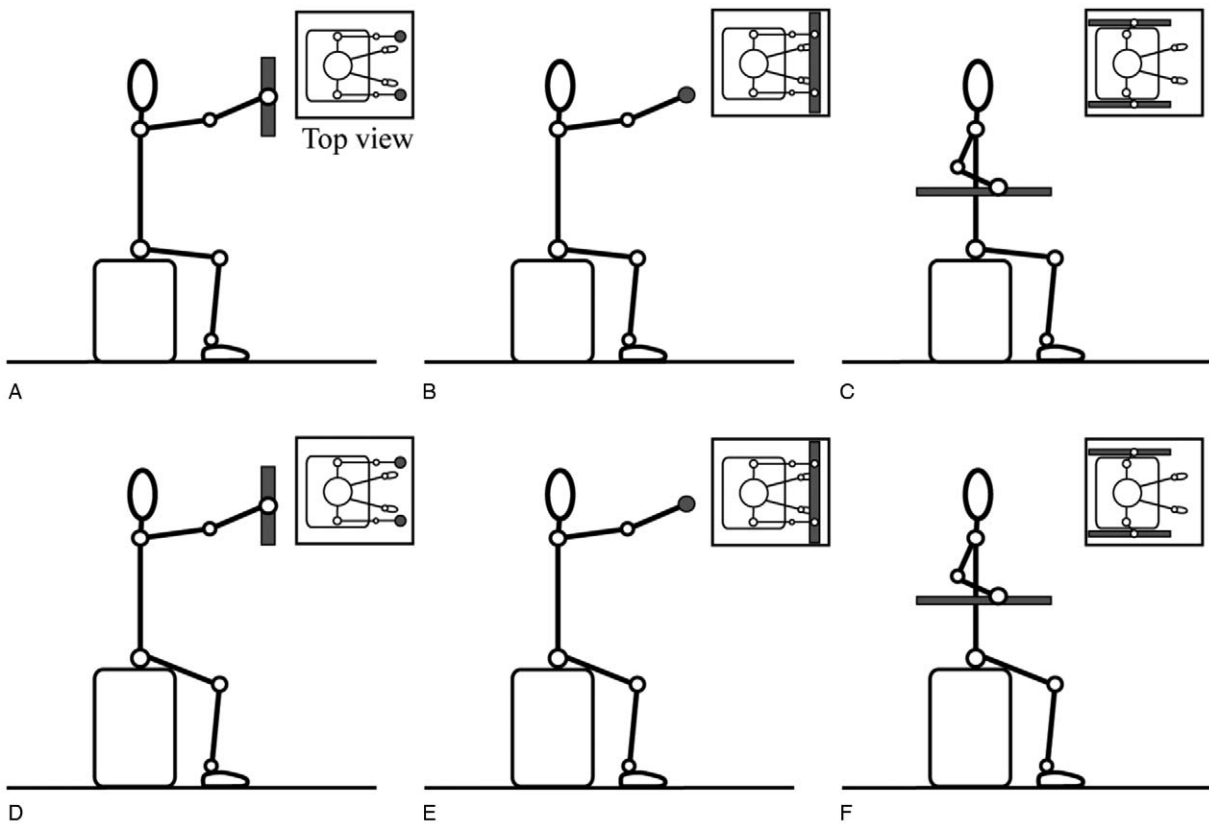


Figure 3. Test conditions: (A) LSVH, (B) LSHH, (C) LSBH, (D) HSVH, (E) HSHH, (F) HSBH. BH = bilateral handrail, HH = horizontal handrail, HS = high seat, LS = low seat, VH = vertical handrail.

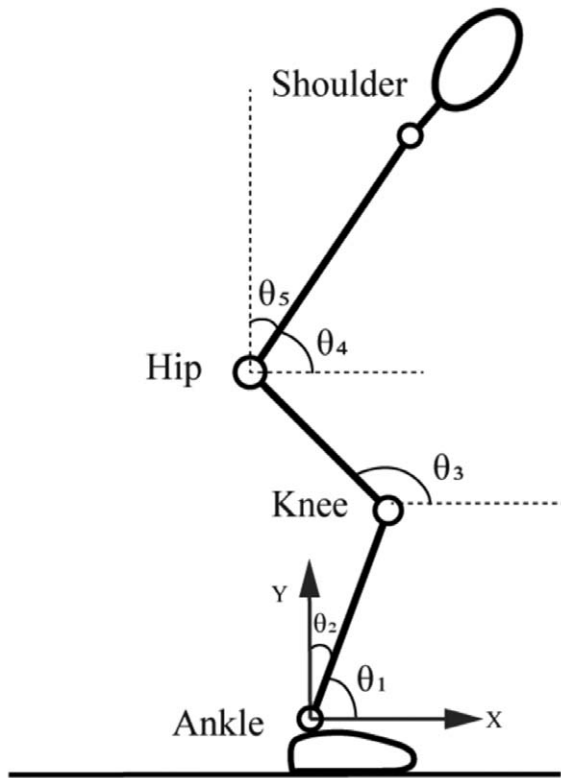


Figure 4. Link segment model in the sagittal plane (θ_1 ankle angle, θ_2 ankle dorsiflexion angle, θ_3 knee angle, θ_4 hip angle, θ_5 trunk tilt angle).

example, when it was found that the test data of a particular measurement was clearly wrong, we remeasured the data.

2.4. Data analysis

After recording the STS movement process using a high-definition camera, we used Adobe Photoshop 2018 (Adobe Systems

Software; Ireland) to extract each frame of the video. We established a coordinate system of the human body in the sagittal plane with the ankle joint as the coordinate origin, the forward direction of the body as the positive direction of the X axis, and the upward direction of the body as the positive direction of the Y axis. Then, the pixel coordinates of the knee, hip, and shoulder joints were obtained, and the actual coordinates of each joint were obtained through calibration. We established a link segment model (including foot, shank, thigh, and trunk [including head]) in the sagittal plane with the ankle joint as the origin for kinematic analysis (Fig. 4). The shank, thigh, and trunk angles were expressed as the absolute angles of the segments regarding the horizontal line of a global reference coordinate system. We used the actual coordinates of adjacent joints to calculate the rotation angle of the shank, thigh, and trunk. All the kinematic data were time-normalized to the cycle duration set to 100%. Regarding the plantar pressure analysis, it was assumed that the subjects' left and right plantar pressures were symmetrical. The plantar pressure data used in this study referred to the average plantar pressure of the left and right feet, and all plantar pressure data were normalized to each subject's body weight.

All of the above kinematics and pressure data were the average of 3 trials, and all curves were fitted using Origin 2018 (OriginLab, Northampton, MA) spline fitting to make them smoother.

STS movement was divided into 4 phases (Fig. 5): phase I, the flexion-momentum phase (between T0 and T1), began with initiation of the movement ($\Delta\theta_5 > 0.1$) and ended just before the buttocks were lifted from the seat ($\Delta\theta_3 > 0.6$); phase II, the momentum-transfer phase (between T1 and T2), began with the buttocks being lifted from the seat and ended when the maximum ankle dorsiflexion was achieved (maximum θ_2); phase III, the extension phase (between T2 and T3), initiated just after maximal ankle dorsiflexion and ended when the hip first ceased to extend (maximum θ_4); phase IV, the stabilization phase (between T3 and T4), began when the hip first ceased to extend and continued until STS movement was completed ($\Delta\theta_4 < 0.1$). Because the time and performance of phase IV varied substantially between individuals

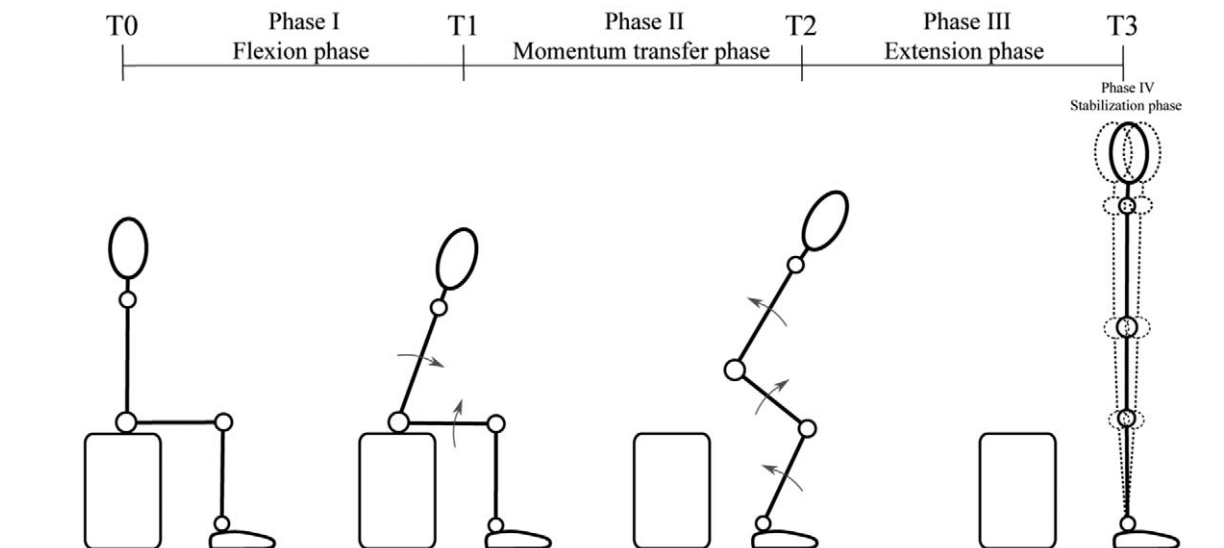


Figure 5. Four phases of STS.

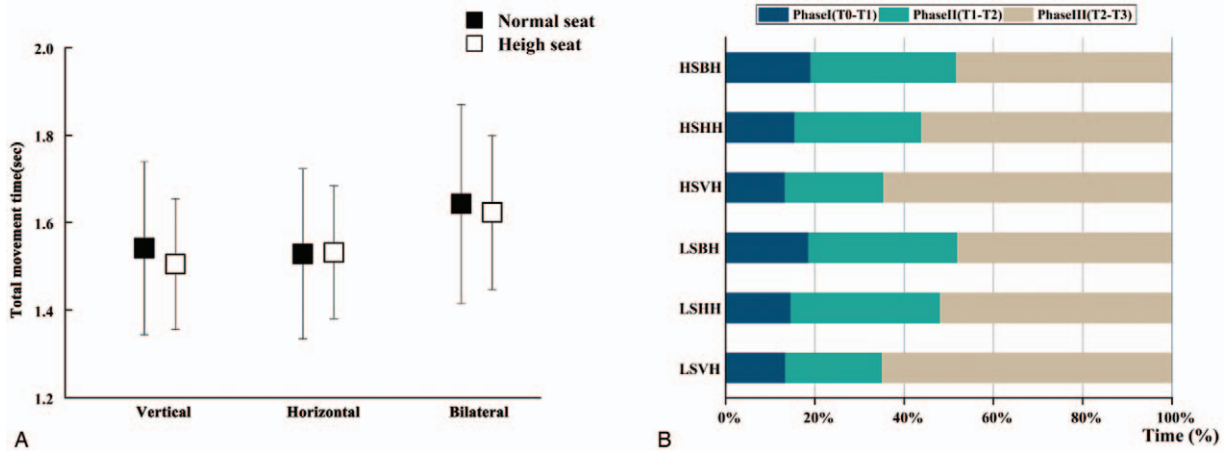


Figure 6. (A) Total movement time of STS. (B) Percentages of movement time in 3 phases of STS movement. STS = sit-to-stand.

during STS, the present study mainly considered the data of phases I, II, and III. The phase IV data were not specifically analyzed in this study.

2.5. Statistical analysis

Data analysis was performed using a statistical software package (SPSS Ver.23, IBM-SPSS Inc., Chicago, IL). The significance level was set at <0.05 . The Shapiro–Wilk test was used to test the normality. The data showed a normal distribution in this study. The effects of handrail type and seat height for the movement time, trunk tilt angle, plantar pressure, and the time from hindfoot to forefoot peak pressure during STS were examined using two-way repeated measures ANOVA, followed by a Bonferroni posthoc test.

3. Results

3.1. Movement time

The mean and standard deviation of the total movement time and percent of movement time in each phase are illustrated in Figure 6 and Table 2. We observed that the total movement time of STS was independently influenced by handrail type ($P < .001$) and seat height ($P < .02$). Posthoc tests revealed a significant difference between LSVH and LSBH (1.54 seconds vs 1.64 seconds; $P = .014$), LSHH and LSBH (1.53 seconds vs 1.64 seconds; $P = .012$), HSVH and HSBH (1.46 seconds vs 1.58 seconds; $P = .002$), HSHH and HSBH (1.48 seconds vs 1.58 seconds; $P = .019$), and LSVH and HSVH (1.54 seconds vs 1.46 seconds; $P = .007$) conditions. In addition, the percentage of movement time at phases I ($P = .004$), II ($P < .001$), and III ($P < .001$) were only influenced by handrail type.

3.2. Joint angles

The hip, knee, and ankle angles at each transitional point (T1, T2, and T3) of STS movement and the maximum trunk tilt angle are shown in Table 2. There was no interaction between handrail type and seat height for the joint angles. Maximum trunk tilt angles ($P < .001$) were only influenced by handrail type. Posthoc tests revealed a significant difference between LSVH and LSBH

(14.85° vs 28.56° ; $P < .001$), LSHH and LSBH (13.93° vs 28.56° ; $P < .001$), HSVH and HSBH (13.98° vs 28.20° ; $P < .001$), and HSHH and HSBH (14.02° vs 28.20° ; $P < .001$) conditions. In addition, at the T1 transitional point, ankle angles were only influenced by handrail type ($P < .001$); with respect to the knee, hip, and trunk angles, they were independently influenced by handrail type ($P < .001$) and seat height ($P < .001$). At the T2 transitional point, ankle angles ($P < .001$) were independently influenced by handrail type ($P < .001$) and seat height ($P = .001$), knee angles were only influenced by seat height ($P = .003$), and hip and trunk angles were only influenced by handrail type ($P < .001$). There were no significant differences between conditions for the joint angles at the T3 transitional point.

3.3. Plantar pressure

The plantar pressure changes during STS are illustrated in Figure 7. The plantar pressure at each transitional point (T1, T2, and T3) of STS movement and the maximum plantar pressure of the STS progress are shown in Table 2. We found that there was no significant difference in the maximum plantar pressure between 6 conditions ($P > .05$), and the moment when the maximum plantar pressure was generated was close to T3. At the T1 transitional point, plantar pressure was independently influenced by handrail type ($P = .016$) and seat height ($P = .039$). At the T2 transitional point, plantar pressure was only influenced by handrail type ($P = .006$).

The times from hindfoot to forefoot peak pressure during STS movement are illustrated in Figure 8 and Table 2. We observed that there was an interaction between handrail type and seat height for the time from hindfoot to forefoot peak pressure of STS ($P = .003$). There was a significant difference between LSHH and LSVH, LSHH and LSBH, HSHH and HSVH, and HSHH and HSBH ($P < .001$, $\eta_p^2 = 0.972$) conditions. There was also a significant difference between LSVH and HSVH, LSHH and HSHH, and LSBH and HSBH ($P < .001$, $\eta_p^2 = 0.962$) conditions.

4. Discussion

The main objective of this study was to investigate the effect of different handrail types and seat heights on kinematics and plantar pressure in healthy young adults during STS. We found

Table 2
Movement time, ankle, knee, hip, and trunk angle, plantar pressure during STS in each condition.

	LSVH	LSHH	LSBH	HSVH	HSHH	HSBH	P-value		
							Handrail type	Seat height	Handrail type × seat height
Total time of movement (s)	1.54±0.20	1.53±0.19	1.64±0.23 ^{†,‡}	1.46±0.16 [#]	1.48±0.17	1.58±0.19 ^{,¶}	<.001	.02	.591
Movement time in phase I (%)	13.39±5.92	14.63±7.33	18.54±7.10 ^{†,‡}	13.30±6.41	15.48±8.30	19.06±6.34 ^{,¶}	.004	.699	.669
Movement time in phase II (%)	21.66±14.02	33.39±13.25 [*]	33.44±8.58 [†]	22.07±19.93	28.36±12.49 [§]	32.63±11.82	<.001	.691	.336
Movement time in phase III (%)	64.95±12.78	51.98±12.11 [*]	48.02±7.06 ^{†,‡}	64.63±14.54	56.16±13.19	48.31±11.62 ^{,¶}	<.001	.576	.671
Ankle angle (°)									
T1	80.86±4.73	78.19±4.47	79.07±4.63	81.69±4.05	79.46±3.64	78.87±5.33	.132	.284	.566
T2	78.52±4.45	74.03±5.22 [*]	70.94±4.32 ^{†,‡}	80.20±3.90	76.21±4.23 [§]	74.03±4.57	<.001	.001	.650
T3	85.77±2.56	85.54±2.54	84.85±3.19	85.2±2.76	85.21±2.64	85.41±3.12	.920	.756	.336
Knee angle (°)									
T1	170.71±3.84	166.57±3.56	166.64±4.60	160.56±3.76 [#]	157.01±3.83 ^{**}	156.65±4.28 ^{††}	.141	<.001	.839
T2	149.05±14.16	140.01±14.23	139.14±8.77	139.54±17.43 [#]	135.24±8.77	135.49±8.92	.077	.003	.278
T3	90.19±3.57	89.76±3.89	89.5±5.03	90.69±3.16	90.13±3.04	89.88±5.55	.106	.439	.993
Hip angle (°)									
T1	84.28±2.64	84.77±3.68	79.04±5.65 ^{†,‡}	86.31±2.35 [#]	85.91±2.12	80.43±4.16 ^{,¶}	<.001	.013	.718
T2	78.17±6.71	79.35±6.44	66.60±5.46 ^{†,‡}	79.86±7.03	77.89±6.04	66.47±6.73 ^{,¶}	<.001	.958	.258
T3	91.51±3.03	92.93±3.36	90.59±4.66	90.88±3.24	93.06±2.86	88.86±5.57	.601	.750	.949
Trunk angle (°)									
Maximum	14.85±6.84	13.93±6.73	28.56±5.78 ^{†,‡}	13.98±6.36	14.02±7.55	28.20±6.90 ^{,¶}	<.001	.371	.688
T1	5.72±2.64	5.23±3.68	10.96±5.65 ^{†,‡}	3.69±2.35 [#]	4.09±2.12	9.57±4.16 ^{,¶}	<.001	.013	.718
T2	11.83±6.71	10.65±6.44	23.40±5.46 ^{†,‡}	10.14±7.03	12.11±6.04	23.53±6.73 ^{,¶}	<.001	.958	.258
T3	-0.70±2.04	-0.53±1.74	-0.90±1.89	-0.93±1.65	-0.43±2.21	-0.55±2.50	.601	.750	.949
Plantar pressure(kg/body weight)									
Maximum	0.027±0.006	0.025±0.005	0.028±0.006	0.025±0.007	0.028±0.007	0.026±0.008	.685	.113	.187
T1	0.008±0.006	0.007±0.006	0.005±0.004 ^{†,‡}	0.007±0.007	0.004±0.004 ^{**}	0.004±0.005	.016	.039	.253
T2	0.023±0.009	0.023±0.012	0.017±0.007 ^{†,‡}	0.021±0.008	0.022±0.012	0.017±0.007 ^{,¶}	.006	.270	.396
T3	0.026±0.010	0.025±0.012	0.027±0.016	0.025±0.006	0.026±0.013	0.023±0.010	.968	.151	.167
Time from hindfoot peak to forefoot peak (%)	34.27±3.31	22.53±1.22 [*]	32.90±3.12 [‡]	21.64±2.81 [#]	14.23±2.01 ^{§,***}	22.34±2.57 ^{,††}	<.001	<.001	.003

BH = bilateral handrail, HH = horizontal handrail, HS = high seat, LS = low seat, STS = sit-to-stand, VH = vertical handrail.

* Significant difference between LSVH and LSHH (P < .05).

† Significant difference between LSVH and LSBH (P < .05).

‡ Significant difference between LSHH and LSBH (P < .05).

§ Significant difference between HSVH and HSHH (P < .05).

|| Significant difference between HSVH and HSBH (P < .05).

¶ Significant difference between HSHH and HSBH (P < .05).

Significant difference between LSVH and HSVH (P < .05).

** Significant difference between LSHH and HSHH (P < .05).

†† Significant difference between LSBH and HSBH (P < .05).

that the total movement time and maximum trunk tilt angle during STS were independently influenced by handrail type and seat height. Regarding the time from hindfoot to forefoot peak pressure of STS, there was an interaction between handrail type and seat height.

For the total movement time, the VH or HH took 0.10 to 0.12 seconds less time to accomplish the STS movement than when using BHs. This result was due to the subjects pulling the handrails when using the VH or HH to reach the standing position faster.

The maximum trunk tilt angle during STS movement when using the BHs was 13.71° to 14.63° larger than when using VH or HH. The reason for this finding may be that the horizontal and VHs limited the bending of the trunk because they were both set in front of the subjects. These kinds of characteristics were found to be similar to the results of a previous study noting that the front support does have some practical and psychological disadvantages because some subjects nearly bumped their heads against it, and some participants also felt locked in by this front support.^[6]

Sato et al^[5] pointed out that the time from hindfoot to forefoot peak pressure could be the most suitable indicators of STS motion difficulty. The results of our study indicated that under LS conditions, the time from hindfoot to forefoot peak pressure when using HHs was 32% to 34% shorter than when using VH or BH; furthermore, under HS conditions, the time from hindfoot to forefoot peak pressure when using HHs was 34% to 36% shorter compared with using VH or BH. Hence, the subjects could complete the STS movement more easily using HHs. In addition, under VH or HH conditions, the time from hindfoot to forefoot peak pressure when using a HS was 37% shorter than when using a LS, and under BH conditions, the time from hindfoot to forefoot peak pressure when using a HS was 32% shorter compared with using a LS. Therefore, the subjects had less difficulty standing in HS conditions than in LS conditions, in accordance with Weiner et al^[25] research. In general, the time from hindfoot to forefoot peak pressure was shortest under HSHH condition. We assumed subjects could reach steady state quickly in this condition.

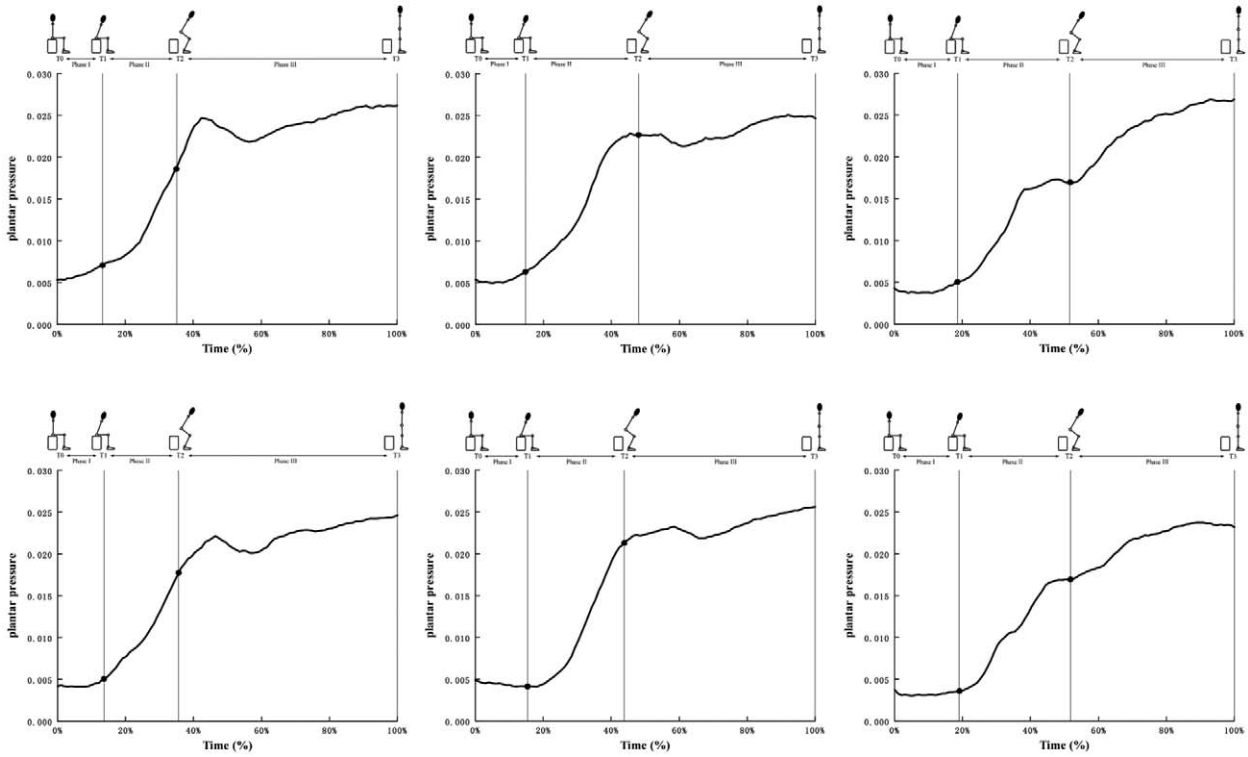


Figure 7. Changes in plantar pressure during STS in 6 conditions. STS = sit-to-stand.

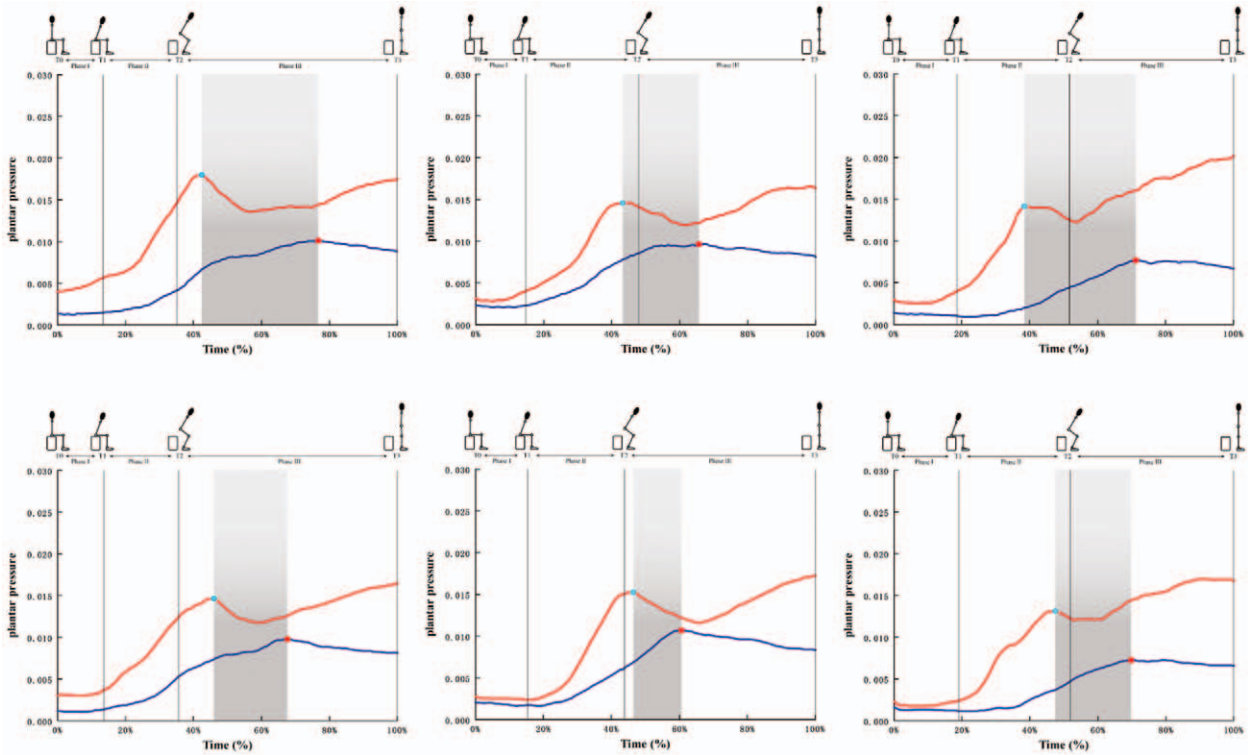


Figure 8. Changes in plantar pressure of the hindfoot and forefoot during STS in 6 conditions. STS = sit-to-stand.

When considering the flexion-momentum phase, the results revealed that the movement time in this phase was 27% to 43% longer when using BHs compared with using VH or HHs. At the end of the flexion-momentum phase (T1), the trunk tilt angle when using BHs was 5.24° to 5.88° larger than when using VH or HH. More upper-body momentum was, therefore, generated when using BHs in phase I,^[1] and the knee joint load was reduced in this manner.^[26]

At the end of the momentum-transfer phase (T2), the ankle angle when using BHs was 3.09° to 7.58° smaller than when using VH or HH, and the trunk tilt angle when using the BHs was 11.42° to 13.39° larger compared with using the VH or HH. This may be because that there was no obstacle in front of the subjects that prevented them from standing. Trunk and shank both tilted forward at a large angle under BH condition. Thus, the whole-body center-of-gravity could shift a greater distance anterior when using BHs, resulting in an increased risk of falling.^[1] The plantar pressure when using BHs was 26% smaller than when using VH or HH. The reason for this finding may be that BHs provided much more grasp reaction force in upward direction at T2, and it might reduce the lower limb load.^[16,18]

At the end of the extension phase (T3), because the subjects had reached a standing posture, there was no significant difference in the joint angle, and the plantar pressure also tended to a stable value.

Numerous studies have shown that the design of STS assistive devices must be based on the kinematic laws governing STS transfer in healthy young adults.^[27-29] In this study, the movement trajectory of each joint, movement time, and joint angles during STS movement were obtained. The movement trajectory of each joint could provide a basis for us to design the mechanism of an assistive device and determine the degree of freedom of such a device. According to the movement trajectory of each joint, joint angles, and movement time, we could calculate the velocity and angular velocity of each joint, and these values could be used to control the assistive device to realize STS transfer naturally. The data of kinematics and plantar pressure in this study could provide a basis for the design of more comfortable and stable seat, and give a reference for the selection of handrail type and installation position. In addition, clinicians could formulate appropriate rehabilitation training plans for patients and the elderly with weak lower limbs and poor balance based on the data of kinematics and plantar pressure in this study.

In conclusion, this study revealed that STS movement was affected by both handrail type and seat height. Using HSHH could take less time to accomplish STS movement; it also reduced the maximum trunk tilt angle and thus reduce the risk of falling; the time from hindfoot to forefoot peak pressure when using HSHH was short and subjects could accomplish STS movement easier. Although using BHs might reduce the lower limb load, it could increase the risk of falling because the large trunk tilt angle and small ankle angle were produced in this condition. Therefore, we proposed an assisted standing strategy that could be applied to the design of assistive devices; that is, choose to use a HSHH in the assistive device in order to make full use of the arm strength and enable users to more quickly and easily complete STS movements.

This study has limitations because of the subject pool and protocol. First, this study did not analyze the data of subjects in the STS stabilization phase; therefore, the effect of handrail type and seat height in the stabilization phase is still unclear. Second, this study did not consider the joint moment, despite it being an important parameter in STS movement. In future research, an

analysis of the joint moment during STS should be performed. Finally, this study's subjects were healthy young adults, elderly and clinical populations were not considered. Hence, our results cannot be extended to these populations. Selecting a support mode suitable for different populations is the focus of our future research.

Author contributions

Conceptualization: Xiaolong Han, Qiang Xue, Shuo Yang, Shouwei Zhang, Min Li

Formal analysis: Xiaolong Han

Methodology: Xiaolong Han, Qiang Xue

Supervision: Qiang Xue

Visualization: Shouwei Zhang, Min Li

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