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Influence of handrail height and knee joint support on sit-to-stand movement

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Abstract

Handrail height and knee joint support both significantly influence sit-to-stand (STS) movement. However, research on the associations between handrail height, knee joint support, and their cumulative effect on STS kinematics and changes in plantar pressure distribution during STS under different handrail heights and knee joint support is still unclear. The main objective of this study was to examine the influence of handrail height and knee joint support on the kinematics and the distribution of plantar pressure in healthy adults during STS. Twenty-six healthy adult subjects aged 23 to 58 years participated in this experiment. The subjects carried out STS movement experiments under 7 conditions: 6 experimental conditions of 3 different heights of handrail, with and without knee joint support, and 1 control condition of standing up naturally. The motions of the markers were recorded using cameras operating at 60 Hz, and total movement time, the percentage of movement time of each phase, trunk tilt angle, joint angle, plantar pressure, and the time from hindfoot to forefoot peak pressure were analyzed and compared. Handrail height significantly influences the percentage of movement time at phase I (P = .015) and the maximum trunk tilt angle (P < .05), knee joint support significantly influences the maximum trunk tilt angle and ankle angle (P = .033), and handrail height and knee joint support have an interaction on the time from hindfoot to forefoot peak pressure (P < .001). Subjects' STS performance was improved with the use of assistant devices but showed particular improvement under the condition of with knee joint support when the handrail height was middle handrail.

Abbreviations: H1 = low handrail, H2 = middle handrail, H3 = high handrail, KH1 = carried out STS movement with knee joint support when the handrail height was H1, KH2 = carried out STS movement with knee joint support when the handrail height was H2, KH3 = carried out STS movement with knee joint support when the handrail height was H3, NS = stand up naturally, STS = sit-to-stand.

Keywords: handrail height, kinematic analysis, knee joint support, plantar pressure, sit-to-stand

Key Points

- What was done: According to the experimentally collected STS kinematic data of 26 subjects, the differences of the total movement time, the percentage of movement time of each phase, trunk tilt angle, joint angle, plantar pressure, and the time from hindfoot to forefoot peak pressure were analyzed and compared among 7 conditions, and kinematic laws governing STS transfer were summarized.
- What was found: Subjects' STS performance was improved with the use of assistant devices but showed particular improvement under the condition of with knee joint support when the handrail height was H2.

1. Introduction

The sit-to-stand (STS) movement is an essential prerequisite for standing activities and requires strength, coordination, balance, and flexibility in execution.[1–3] Inability to complete this task may necessitate wheelchair use or confine patients to bed, thus accelerating muscle atrophy and muscle strength decline.[4,5] STS assistive devices can help patients with lower limb dysfunction to complete STS movement in daily life, thereby lessening the burden on nursing staff, who may otherwise need to personally assist patients.[6–9] It can also be used to perform STS movement rehabilitation training for patients, so as to delay the decline of body functions to a certain extent, and to gradually restore muscle strength.[10–13] Support is the most significant part of STS assistive devices. In order to ensure user safety, it is necessary to analyze the kinematics, dynamics, and movement strategies of the human body in the STS process.

Use of handrails allow the muscles of the legs to be assisted by the muscles of the arms and may reduce lower limb joint torque,[14] enabling a more stable STS movement. Kinoshita et al[15] investigated the handrail position that best facilitate STS movement and found that "high and low" handrail position

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reduces STS movement time and joint torque. Kinoshita et al[16] also studied the effect of handrail height on STS movement and found that, compared to a control movement without handrails, use of low handrails increased hip flexion angle, ankle dorsiflexion angle, trunk forward tilt angle, and forward shift of center-of-gravity (COG), while use of high handrails decreased hip flexion angle and trunk forward tilt angle. When Qiu et al[17] investigated the effects of handrail grip position on trunk tilt angle during STS movement with the use of bilateral handrails, the results showed that participants experienced the least hip joint torque when the grip position was above the greater trochanter and participants stood up from an erect sitting position resulted, while knee joint torque was minimized by a trunk tilt angle of 30°. Kato et al[18] investigated the difference in handrail reaction force between a curved angled handrail and a conventional vertical handrail when used by the elderly. The findings indicated that the curved angled handrail had greater handrail reaction force than the conventional vertical handrail. Dekker et al[6] studied different support forms within the toilet environment and noted a preference for vertical handrails and bilateral grab bars during STS movement. There have been many other studies on the forms and positions of handrails used in the toilet environment,[6,19,20] but we have not found any studies on the use of handrails higher than the seated acromion height in the literature on STS movement, and handrails lower than the seated acromion height may not make the user better use their strength of upper limbs in rehabilitation training. Moreover, the influence of handrail height on kinematics and plantar pressure during STS movement is still not well understood, and how to set the height of the handrail reasonably is still unclear.

Knee joint support is also an important part of STS assistive devices, and is often used together with the handrail. For the elderly and patients with other mobility issues, standing up is often difficult due to the decline of muscle strength and the limited range of knee flexion, and so support at the knee or shank may improve the effect of STS movement assistance. We have found that there are some devices that include knee joint support,[21–23] but to the best of our knowledge, the kinematics, kinetics, and movement postures of the human body when the knee joint position is restricted have not been studied in depth.

In addition, many studies have used plantar pressure to calculate joint torque and the center of pressure, but studies on the changes in plantar pressure distribution during STS movement are fewer. Sato et al[18] investigated the relationship between the change of plantar pressure distribution and STS performance when using seats of different hardness, and found that the time from hindfoot to forefoot peak pressure could be the best indicator of STS movement difficulty. However, the change of plantar pressure distribution with the use of different handrail heights and knee joint supports is still unclear.

The purpose of this study was to examine the influence of handrail height and knee joint support on the kinematics and the distribution of plantar pressure in healthy adults during STS. The knowledge gained from this study may be used to evaluate potential therapeutic uses of STS transfer devices in rehabilitation; therefore, the elderly and clinical populations could benefit from this study.

We first hypothesized that the use of handrails and knee joint support during STS movement would restrict the forward tilt angle of the trunk. Secondly, we hypothesized that the use of handrails and knee joint support would change the percentage of movement time at each phase of STS movement. Finally, we hypothesized that the use of handrails and knee joint support would change the time from hindfoot to forefoot peak pressure during the STS movement.

2. Method

2.1. Participants

In this study, we recruited 26 healthy adult males aged 23 to 58 at Tianjin University of Science and Technology, including students and teachers. Further information on the subjects is shown in Table 1. The inclusion criteria were that subjects could complete STS independently. People who had undergone any major orthopedic surgery, suffered from neurological diseases or musculoskeletal problems, or had any sensory, visual, auditory, or cognitive impairment were excluded. The 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.

2.2. Instrumentation

According to the preliminary investigation, seat heights for STS movement experiments are usually between 400 mm and 470 mm. In this study, the experimental setup included a seat height of 415 mm, parallel vertical handrails placed in front of the subjects at shoulder-width apart, and handrail height settings that could be adjusted to low handrail (H1), middle handrail (H2), or high handrail (H3), corresponding to 110%, 120%, and 130% seated acromion height of each subject, respectively. A detachable support plate was then set at the level of the subjects' knee joint (Fig. 1). We placed the high definition camera (4096 × 2160 pixel, 60fps/s; EOS 200D II, Canon) on the left side of the subjects to collect kinematic data in the sagittal plane, and used flexible film pressure sensors (MD30-60, Leanstar, Suzhou, China) to obtain plantar pressure. Film pressure sensors are a kind of resistance sensor whose output resistance decreases as the pressure applied on the sensor surface increases. The plantar pressure can be measured through a specific pressure resistance relationship to convert the electrical signal into the pressure value. Flexible film pressure sensors were placed on the subjects' forefeet and hindfeet, and in order to ensure the accuracy of the sensors, subjects were asked to complete the STS movement barefoot.

2.3. Protocol

This study is observational. Subjects were asked to wear tight black clothing to allow better motion capture. In order to record the movement trajectories of joints accurately, the markers were attached to the following anatomical landmarks on the left side of the subject's body: shoulder, waist, knee, hip, and ankle joints. When perform STS movement, the subjects were asked to sit on a backless and armless chair with their backs straight and their feet naturally placed on the ground. Then began to stand up at the word "start," while the pressure sensors and high-definition camera recorded the data simultaneously. The movement ended with the subject's self-reported "stop," when they had achieved an erect position and no longer swayed.

The subjects were asked to carry out the STS movement experiment under 7 conditions. First, subjects were instructed to fold their arms across the chest and stand up naturally (NS). This served as the control motion. Then 6 experimental conditions with various supports were implemented in a randomized way to avoid bias (Fig. 2). Under each of these conditions (respectively), subjects:

(1) Carried out STS movement without knee joint support when the handrail height was H1
(2) Carried out STS movement without knee joint support when the handrail height was H2

Table 1

Information on subjects.

Age (yr)	Height (cm)	Weight (kg)	BMI (kg/m²)
26.9 ± 6.5	174.4 ± 6.5	69.0 ± 8.7	22.7 ± 2.7

Mean ± standard deviation (SD).

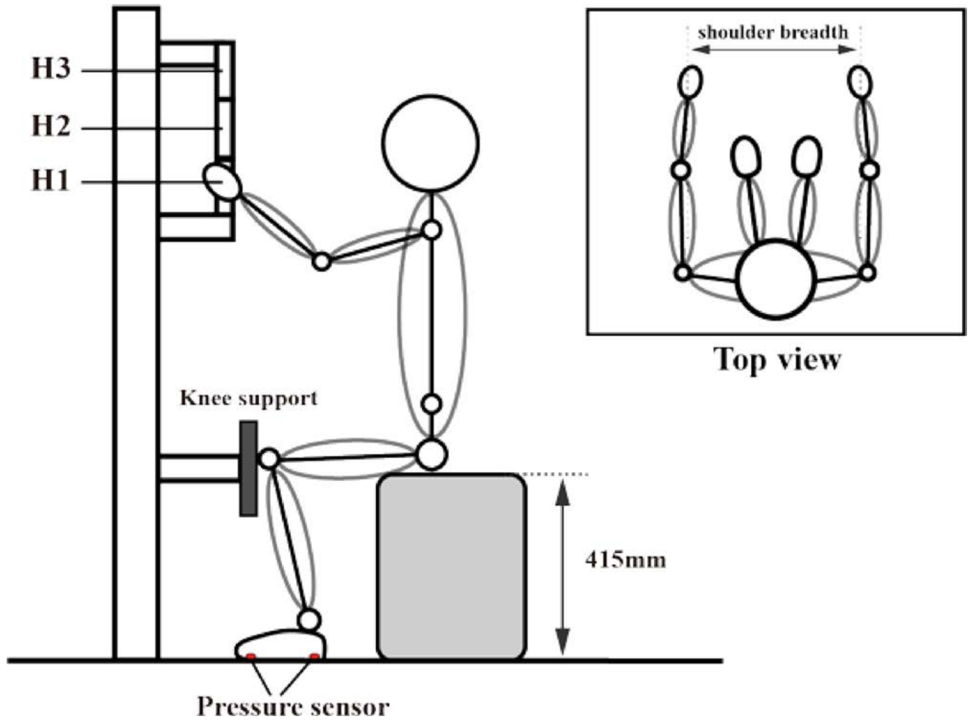

Figure 1. Experiment equipment. (H1: Low handrail; H2: Middle handrail; H3: High handrail). H1 = low handrail, H2 = middle handrail, H3 = high handrail.

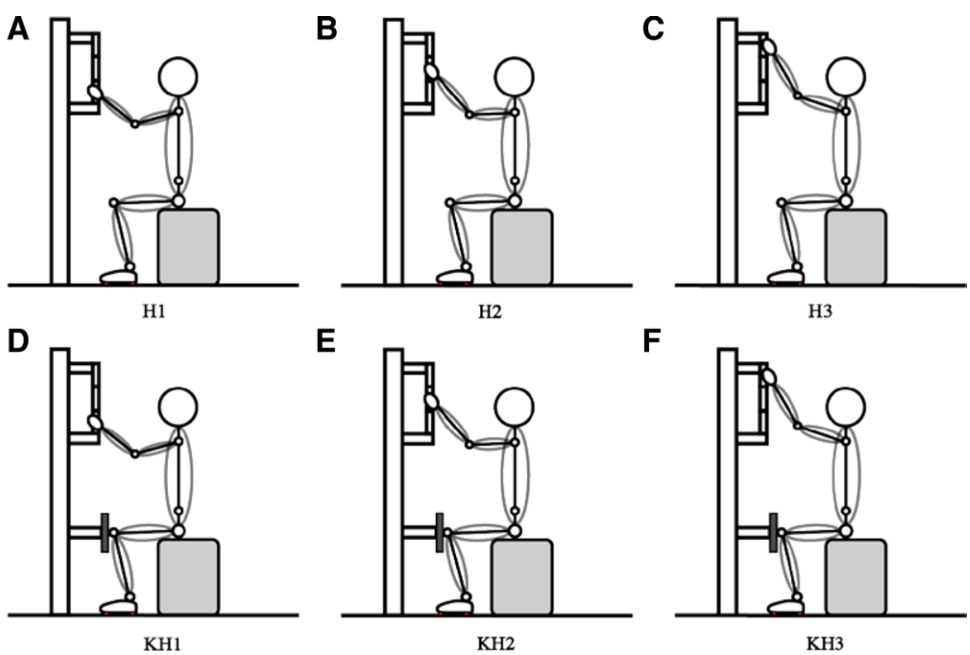

Figure 2. Experimental conditions.

(3) Carried out STS movement without knee joint support when the handrail height was H3
(4) Carried out STS movement with knee joint support when the handrail height was H1
(5) Carried out STS movement with knee joint support when the handrail height was H2
(6) Carried out STS movement with knee joint support when the handrail height was H3

Before beginning the experiment under each condition, subjects were given 2 practices of STS, and the experimental setup was adjusted. Then 3 trials of the STS task were conducted and subjects rested for an appropriate amount of time between each trial.

2.4. Data analysis

We used Adobe Photoshop 2018 (Adobe Systems Software; Ireland) to extract each frame of the video. Then 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.

In order to facilitate the analysis, we established a simplified unilateral model in the sagittal plane, as shown in Figure 3. The link segment model contained 4 rigid bodies connected by 3 joints (including feet, shanks, thighs, and trunk). The angles between the horizontal plane and shank, thigh, and trunk were defined as θ_1, θ_3, and θ_4, and were calculated using the actual coordinates of adjacent joints. All the kinematic data were time-normalized. We 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, USA) spline fitting to make them smoother.

STS movement was divided into 4 phases (Fig. 4). Phase I, the flexion-momentum phase (between T0 and T1), began with initiation of movement ($\Delta\ \theta_5 > 0.1^\circ$) and ended just before the buttocks were lifted from the seat ($\Delta\ \theta_3 > 0.6^\circ$). Phase II, the momentum-transfer phase (between T1 and T2), began when the buttocks lifted from the seat and ended when the shank started to bend backwards ($\Delta\,\theta_2 > 0.6^\circ$). Phase III, the extension phase (between T2 and T3), initiated just after the shank started to bend backwards 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 the STS movement was completed ($\Delta\ \theta_4 < 0.1^\circ$). Because the time and performance of phase IV varied greatly between individuals, the end point of phase IV was not easily defined. We therefore did not specifically analyze phase IV in this study. For the purposes of this article, and for calculations, we have considered only phases I, II, and III.

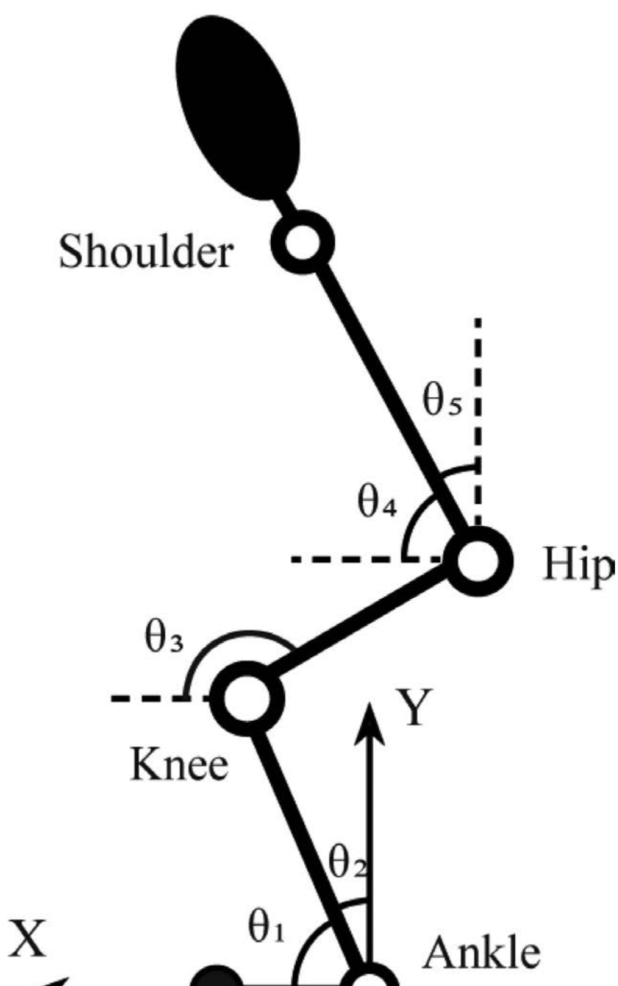

Figure 3. Link segment model in the sagittal plane. (θ_1 ankle angle, θ_2 ankle dorsiflexion angle, θ_3 knee angle, θ_4 hip angle, θ_5 trunk tilt angle).

2.5. Statistical analysis

Data analysis was performed using a statistical software package (SPSS Ver.18, 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 movement time, the percentage of movement time at each phase, trunk tilt angle, joint angle, plantar pressure, and time from hindfoot to forefoot peak pressure during STS under the NS condition and the H1, H2, H3, carried out STS movement with knee joint support when the handrail height was H1 (KH1), carried out STS movement with knee joint support when the handrail height was H2 (KH2), carried out STS movement with knee joint support when the handrail height was H3 (KH3) conditions were compared by independent samples *t*-test. The effects of handrail height and knee joint support within those parameters were examined using 2-ways repeated measures ANOVA, followed by a Bonferroni post hoc test.

3. Results

Total movement time, the percentage of movement time of each phase, trunk tilt angle, joint angle, plantar pressure, and time from hindfoot to forefoot peak pressure are displayed as mean ± standard deviation (SD) in Table 2.

3.1. Movement time

There was no significant difference in total movement time among the 7 conditions ($P > .05$). The percentage of movement time at phase I was only influenced by handrail height ($P = .015$), and was lower under the high handrail condition than under the low and middle handrail conditions, and there was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$). For the percentage of movement time at phase II, no significant difference was observed among the 7 conditions ($P > .05$). The percentage of movement time at phase III was only influenced by handrail height ($P = .044$), and was higher under the high handrail condition than under the low and middle handrail conditions, and there was a significant increase between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$).

3.2. Trunk tilt angle and joint angles

We observed that the maximum trunk tilt angle was influenced by handrail height (all $P < .05$), and was greater under the low handrail condition than under the high and middle handrail conditions. The maximum trunk tilt angle was also influenced by knee joint support ($P = .033$), and was greater under conditions without knee joint support than under conditions with knee joint support. There was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$).

At the T1 transitional point, no significant difference in trunk tilt angle was observed among the H1, H2, H3, KH1, KH2, and KH3 conditions ($P > .05$), there was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$). For ankle and knee angle, there was no difference among the 7 conditions ($P > .05$).

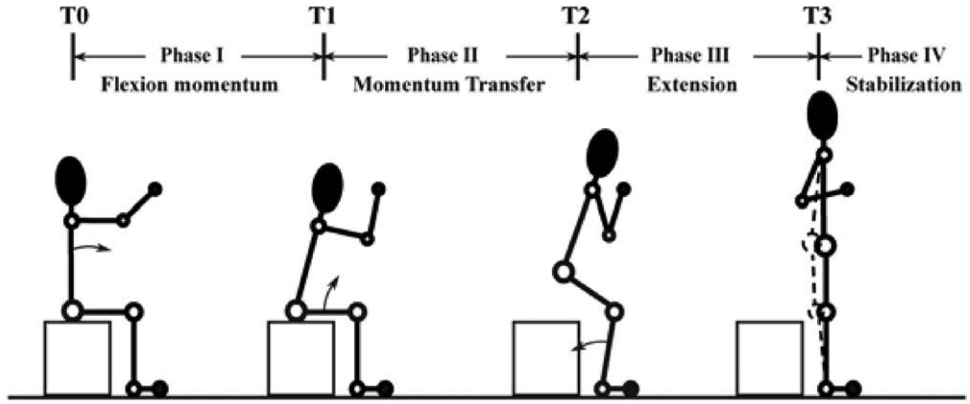

Figure 4. Four phases of STS. STS = sit-to-stand.

At the T2 transitional point, no significant differences in trunk tilt angle were observed among the H1, H2, H3, KH1, KH2, and KH3 conditions ($P > .05$), but there was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$). Ankle angle was only influenced by knee joint support ($P = .006$), and was smaller under conditions without knee joint support than under conditions with knee joint support. There was a significant increase between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$). Knee angle was also only influenced by knee joint support ($P = .042$), and was greater under conditions without knee joint support than under conditions with knee joint support. In addition, there was a significant increase between the NS and the H1, H2, and H3 conditions (all $P < .05$), but no significant difference between the NS and the KH1, KH2, and KH3 conditions (all $P > .05$).

At the T3 transitional point, there was no significant difference in trunk tilt angle among the 7 conditions ($P > .05$). For ankle angle, no significant differences were observed among the H1, H2, H3, KH1, KH2, and KH3 conditions ($P > .05$), but there was a significant increase between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$). For knee angle, there was no significant difference among the 7 conditions ($P > .05$).

3.3. Plantar pressure

There was no significant difference in plantar pressure at the T1, T2, and T3 transitional points among the 7 conditions ($P > .05$). For the maximum plantar pressure, no significant difference was observed among the H1, H2, H3, KH1, KH2, and KH3 conditions ($P > .05$), but there was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .05$).

The variations in hindfoot and forefoot plantar pressure and the time from hindfoot to forefoot peak pressure during STS are illustrated in Figure 5. There was an interaction between handrail height and knee joint support for the time from hindfoot to forefoot peak pressure ($P < .001$). There was a significant difference between the H2 and KH2 conditions (23.63 ± 1.38% vs 30.37 ± 1.19%; $P < .001$), but no significant difference between H1 and KH1 (30.11 ± 3.17% vs 32.23 ± 2.96%; $P < .001$), or between H3 and KH3 (29.25 ± 2.32% vs 32.66 ± 3.09%; $P < .001$). There was a significant difference between the KH2 and the KH1 and KH3 conditions ($P < .001$), but no significant difference between the H1 and the H2 and H3 conditions ($P > .05$). In addition, there was a significant decrease between the NS and the H1, H2, H3, KH1, KH2, and KH3 conditions (all $P < .001$).

4. Discussion

The purpose of this study was to examine the influence of handrail height and knee joint support on the kinematics and the distribution of plantar pressure in healthy adults during STS. The results showed that handrail height significantly influences the percentage of movement time at phase I and the maximum trunk tilt angle, and that knee joint support significantly influences the maximum trunk tilt angle and ankle angle. Handrail height and knee joint support together have an interaction on the time from hindfoot to forefoot peak pressure.

The percentage of movement time at phase I under the H1, H2, H3, KH1, KH2, and KH3 conditions was 3.9% to 11.1% lower than that of under the NS condition. Handrails can provide upward force to subjects and help them leave the chair faster, thereby reducing the percentage of movement time spent at phase I. The percentage of movement time at phase I under the high handrail conditions was 3.7% to 6.1% lower than that of under the low and middle handrail conditions. When subjects used the high handrail, the angle between the subject's arm and the horizontal was greater, and the upward force provided by handrail was greater, thus the percentage of movement time at phase I was lowest under the high handrail condition. Previous studies have suggested that the most difficult phase of STS is nearby seat-off.[16,24,25] Therefore, we believe that the use of high handrails can reduce the time spent in this dangerous phase.

The maximum trunk tilt angle under conditions H1, H2, H3, KH1, KH2, and KH3 was 25.3° to 30.7° smaller than that of under the NS condition, though this may be because the handrail set in front of subjects affects them psychologically and limits the bending of the trunk.[6] The maximum trunk tilt angle under the high handrail condition was 2.74° to 3.33° smaller than that of under the low handrail condition. Since high handrails provided the greatest upward force, they greatly reduced the hip joint torque required for subjects to stand. In our previous studies, we found that the smaller the joint torque, the smaller the change range of the corresponding joint angle. Therefore, the maximum trunk tilt angle under the high handrail condition was the smallest. In addition, the maximum trunk tilt angle under conditions with knee joint support was 2.09° to 4.33° smaller than that of under conditions without knee joint support. We observed that the forward movement range of subject's COG decreased under conditions with knee joint support, thus reducing the maximum trunk tilt angle.

At T2, we observed that subjects' shank movement range decreased due to the limitation of the handrail; the ankle angle under the H1, H2, H3, KH1, KH2, and KH3 conditions was 9.62° to 13.36° > that of under the NS condition. Subjects' shank cannot be bent under conditions with knee joint support, and so the ankle angle under these conditions was 2.93° to 3.74° > that of under conditions without knee joint support. In addition, at T2, we found that subjects' COG was in the back position when only using the handrail. Therefore, the knee angle

Table 2

Movement time; ankle, knee, hip, and trunk angle; plantar pressure during STS under each condition.

	NS	H1	H2	H3	KH1	KH2	KH3	*P*-value		
								Handrail height	Knee support	Handrail type * Seat height
Total time of movement (s)	1.59 ± 0.20	1.52 ± 0.14	1.55 ± 0.20	1.49 ± 0.17	1.54 ± 0.17	1.52 ± 0.17	1.54 ± 0.17	$P = .724$	$P = .273$	$P = .226$
Movement time in phase I (%)	25.44 ± 8.08	20.33 ± 6.42[a]	19.22 ± 5.48[a]	14.26 ± 3.28[a,b,c]	21.56 ± 5.32[a]	20.54 ± 4.24[a]	16.81 ± 6.81[a,e,f]	$P = .015$	$P = .197$	$P = .179$
Movement time in phase II (%)	24.46 ± 5.79	20.68 ± 14.96	18.71 ± 9.33	20.13 ± 11.21	22.25 ± 11.25	21.99 ± 13.25	20.94 ± 11.42	$P = .484$	$P = .091$	$P = .592$
Movement time in phase III (%)	50.10 ± 6.82	58.99 ± 11.45[a]	62.07 ± 9.94[a]	65.61 ± 16.35[a,b,c]	56.19 ± 11.16[a]	57.47 ± 12.93[a]	62.25 ± 12.57[a,e,f]	$P = .044$	$P = .174$	$P = .956$
Ankle angle (deg)										
T1	75.92 ± 6.24	79.05 ± 5.26	79.48 ± 5.21	79.81 ± 4.68	78.92 ± 2.80	78.92 ± 3.51	79.61 ± 4.08	$P = .691$	$P = .705$	$P = .966$
T2	67.12 ± 4.50	76.74 ± 4.67[a]	77.31 ± 4.94[a]	78.62 ± 4.58[a]	79.90 ± 2.95[a]	79.67 ± 3.54[a,c]	80.48 ± 3.95[a,d]	$P = .232$	$P = .006$	$P = .751$
T3	81.75 ± 2.11	86.76 ± 2.23[a]	86.03 ± 2.47[a]	87.06 ± 1.68[a]	86.00 ± 2.22[a]	86.55 ± 2.77[a]	86.40 ± 2.66[a]	$P = .548$	$P = .516$	$P = .342$
Knee angle (deg)										
T1	167.45 ± 4.37	168.49 ± 4.26	167.27 ± 4.02	168.18 ± 3.77	168.51 ± 3.05	168.37 ± 4.25	167.42 ± 4.44	$P = .172$	$P = .804$	$P = .053$
T2	143.36 ± 7.38	153.05 ± 8.42[a]	152.17 ± 10.82[a]	153.26 ± 15.84[a]	139.21 ± 13.75[b]	147.5 ± 16.21[c]	145.98 ± 10.68[d]	$P = .389$	$P = .042$	$P = .056$
T3	89.88 ± 6.79	94.11 ± 2.98	91.59 ± 4.72	93.64 ± 2.56	93.08 ± 4.12	94.90 ± 4.91	94.20 ± 4.45	$P = .568$	$P = .183$	$P = .071$
Trunk angle (deg)										
Maximum	40.94 ± 7.90	15.64 ± 6.81[a,c,d]	14.55 ± 7.24[a]	12.9 ± 6.11[a]	13.55 ± 7.79[a,b,c,d]	10.22 ± 6.49[a,c]	10.80 ± 5.43[a,d]	$P < .001$	$P = .003$	$P = .481$
T1	17.32 ± 10.04	7.17 ± 3.94[a]	7.21 ± 5.24[a]	5.84 ± 4.22[a]	4.24 ± 6.42[a]	4.16 ± 6.11[a]	4.99 ± 3.60[a]	$P = .914$	$P = .063$	$P = .245$
T2	36.89 ± 9.16	13.10 ± 6.96[a]	12.12 ± 6.99[a]	10.14 ± 6.11[a]	11.13 ± 8.21[a]	8.26 ± 7.17[a]	9.11 ± 5.65[a]	$P = .077$	$P = .053$	$P = .207$
T3	-1.07 ± 3.71	-1.18 ± 3.76	-0.21 ± 2.98	-1.85 ± 3.03	-0.36 ± 3.76	-0.59 ± 3.2	-1.69 ± 1.88	$P = .075$	$P = .749$	$P = .395$
Time from hindfoot peak to forefoot peak (%)	42.32 ± 1.89	32.23 ± 2.96[a]	30.37 ± 1.19[a]	32.66 ± 3.09[a]	30.11 ± 3.17[a]	23.63 ± 1.38[a,c,e,g]	29.25 ± 2.32[a]	$P < .001$	$P < .001$	$P < .001$
Plantar pressure(kg/body weight										
Maximum	0.06 ± 0.05	0.04 ± 0.01[a]	0.04 ± 0.02[a]	0.04 ± 0.02[a]	0.03 ± 0.01[a]	0.04 ± 0.02[a]	0.03 ± 0.02[a]	$P = .924$	$P = .115$	$P = .793$
T1	0.02 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	$P = .917$	$P = .0625$	$P = .104$
T2	0.03 ± 0.02	0.03 ± 0.01	0.02 ± 0.01	0.02 ± 0.02	0.02 ± 0.01	0.02 ± 0.01	0.02 ± 0.01	$P = .442$	$P = .751$	$P = .760$
T3	0.03 ± 0.02	0.03 ± 0.01	0.03 ± 0.01	0.03 ± 0.02	0.03 ± 0.01	0.03 ± 0.02	0.03 ± 0.01	$P = .826$	$P = .560$	$P = .473$

[a] Significant difference from NS ($P < .05$).
[b] Significant difference from H1 ($P < .05$).
[c] Significant difference from H2 ($P < .05$).
[d] Significant difference from H3 ($P < .05$).
[e] Significant difference from KH1 ($P < .05$).
[f] Significant difference from KH2 ($P < .05$).
[g] Significant difference from KH3 ($P < .05$).

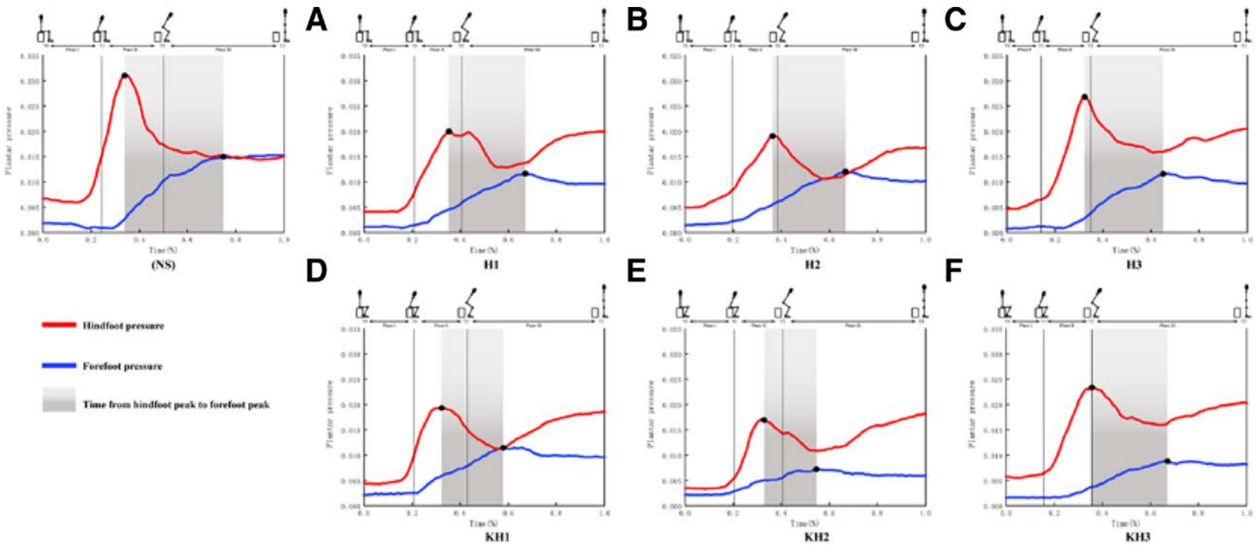

Figure 5. Changes in plantar pressure distribution of the hindfoot and forefoot during STS under the 7 conditions. STS = sit-to-stand.

under the H1, H2, and H3 conditions was 8.81° to 9.90° larger than that of under the NS condition.

The time from hindfoot to forefoot peak pressure under the H1, H2, H3, KH1, KH2, and KH3 conditions was 9.66% to 18.69% shorter than that of under the NS condition, and the time from hindfoot to forefoot peak pressure under KH2 was the shortest. Sato et al[23] suggested that the time from hindfoot to forefoot peak pressure may be the most suitable indicator of STS motion difficulty. If this is taken as true, then the results of our study showed that subjects have the greatest difficulty when standing naturally; in contrast, it was easiest to stand up under the KH2 condition. This would indicate that any assistance method improves STS performance, but methods mirroring that of KH2 are most effective.

In conclusion, the results of this study showed that subjects' STS performance was improved with the use of assistant devices, but showed particular improvement under the KH2 condition. We therefore propose this as an assisted standing strategy that could be applied to the design of assistive devices; that is, devices with knee joint support and handrails at a height of 120% of the user's seated acromion height. Such a device may shorten the time users spend in the most precarious STS phase, allow users to make full use of their arm strength, and enable users to more easily and steadily complete STS movement.

This study has certain limitations. First, this study did not analyze the data of subjects in the stabilization phase of STS, and so the influence of handrail and knee joint support on the stabilization phase remains unclear. Second, this study did not consider joint torque, despite it being an important parameter in STS movement. Finally, this study's subjects were healthy adults, while female, elderly, and clinical populations were not considered. As a result, our findings cannot be extended to these populations. Selecting a support mode suitable for different populations will be the focus of future research.

Author contributions

Conceptualization: Xiaolong Han, Qiang Xue, Shuo Yang, Ya Li, Shouwei Zhang, Min Li.
Formal analysis: Xiaolong Han.
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Supervision: Qiang Xue.
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