Design of a modular postural transition device using a double-parallelogram mechanism

Seyoung Kim[1*], Gildong Hong[1], and Gildong Hong[1]

[1]Advanced Robotics Research Center, Korea Institute of Machinery & Materials (KIMM), Daejeon, South Korea

*Corresponding Author:
Seyoung Kim
Advanced Robotics Research Center, Korea Institute of Machinery & Materials (KIMM)
156 Gajeongbuk-Ro, Yuseong-Gu
Daejeon 305-343
Republic of Korea
Phone: +82-42-868-7614
Email: seyoungkim@kimm.re.kr

keywords: modular postural standing device, robotic chair, postural transition, gravity compensation, optimization

ABSTRACT

In this study.

I. INTRODUCTION

START

II. METHODS

A. Mechanical design of the postural transition device

The postural transition device, capable of performing five distinct types of postural transitions, was designed to be modular, compact, and lightweight. This design sets it apart from traditional embedded postural transition devices, emphasizing its adaptability and scalability. 모듈화를 구현하기 위해

컴팩트를 구현하기 위해

라잇웨잇을 구현하기 위해

B. Gravity compensation with gas springs

C. Postural transitions and return processes

Four subjects, with no history of leg injuries or balance disorders (Male: 3 / Female: 1, mean age: 33±4 years, mean height: 176±13 cm, and mean weight: 75±22 kg)

충남대학교병원 의학연구윤리심의위원회(approval number : CNUH 2020-10-007)

Institutional Review Board for Medical Research Ethics, Chungnam National University Hospital (*CNUH IRB)

D. Power consumption during postural transitions

III. RESULTS

A. Device components moving in sync with postural transitions

B. Theoretical torque advantages of gravity compensation with gas springs

C. Impact of increasing payload on power consumption

65

독립표본 t-test										
	Lifting A	Lifting B	Leaning A	Leaning B	Tilting A	Tilting B	Standing A	Standing B	Rec A	Rec B
1-2	0.11	<0.05	<0.05	<0.05	0.12	<0.05	<0.05	<0.05	0.47	0.61
1-3	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.72	0.42	0.71
1-4	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
1-5	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
2-3	<0.05	0.51	0.61	0.43	<0.05	<0.05	<0.05	<0.05	0.84	0.051
2-4	<0.05	0.52	<0.05	0.51	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
2-5	<0.05	0.64	<0.05	0.36	<0.05	<0.05	<0.05	0.19	<0.05	<0.05
3-4	<0.05	0.22	<0.05	0.77	<0.05	<0.05	<0.05	0.093	<0.05	<0.05
3-5	<0.05	0.98	<0.05	0.069	<0.05	<0.05	<0.05	0.10	0.058	<0.05
4-5-	<0.05	0.40	0.26	<0.05	<0.05	0.16	<0.05	0.81	<0.05	0.46
slope	+	-	+	--	+	+	+	-	-	+
R^2	0.98	0.69	0.97	0.78	0.99	0.96	0.98	0.43	0.90	0.90
p-val	<0.05	0.19	<0.05	0.12	<0.05	<0.05	<0.05	0.47	<0.05	<0.05

66

67

대응표본 t-test										
	Lifting A	Lifting B	Leaning A	Leaning B	Tilting A	Tilting B	Standing A	Standing B	Rec A	Rec B
1-2	0.17	<0.05	<0.05	<0.05	0.16	<0.05	<0.05	<0.05	0.085	0.59
1-3	0.097	<0.05	<0.05	0.10	<0.05	<0.05	<0.05	0.71	0.16	0.64
1-4	<0.05	<0.05	<0.05	0.058	<0.05	<0.05	<0.05	0.063	<0.05	<0.05
1-5	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
2-3	<0.05	0.64	0.37	0.58	<0.05	<0.05	<0.05	0.081	0.76	0.078
2-4	<0.05	0.58	<0.05	0.61	<0.05	<0.05	<0.05	0.097	<0.05	<0.05
2-5	<0.05	0.43	<0.05	0.42	<0.05	<0.05	<0.05	0.22	0.074	<0.05
3-4	<0.05	0.33	<0.05	0.54	<0.05	<0.05	<0.05	0.10	0.074	<0.05
3-5	<0.05	0.99	<0.05	0.16	<0.05	<0.05	<0.05	0.24	0.12	<0.05
4-5-	<0.05	0.50	0.10	0.16	<0.05	0.11	<0.05	0.86	<0.05	0.22
slope	+	-	+	--	+	+	+	-	-	+
R^2	0.98	0.69	0.97	0.78	0.99	0.96	0.98	0.43	0.90	0.90
p-val	<0.05	0.19	<0.05	0.12	<0.05	<0.05	<0.05	0.47	<0.05	<0.05

68

69

IV. DISCUSSION

A. Advantages of ergonomic design in postural transitions

B. Effects of gravity compensation with gas springs on power consumption

C. Limitations of current optimization

ACKNOWLEDGMENTS

This research was supported by the R&D Program at the Korea Institute of Machinery & Materials (KIMM), funded by the National Research Council of Science & Technology.

AUTHOR DECLARATIONS

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Gildong Hong: Methodology (equal); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal). **Gildong Hong**: Writing – review & editing (supporting). **Gildong Hong**: Writing – review & editing (supporting). **Seyoung Kim**: Conceptualization (lead); Methodology (equal); Software (lead); Investigation (equal); Writing – original draft (equal); Writing – review & editing (equal); Visualization (lead); Supervision (lead).

ETHICS APPROVAL STATEMENT

All subjects received sufficient explanation regarding the experiments and signed the informed consent form. The study was approved by the institutional review board of the Korea Advanced Institute of Science and Technology (approval number: CNUH 2020-10-007).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

Table I. System parameters, component specifications and installation conditions, and torque formulas associated with Joint 1

Parameter values used in optimization					
Human subject mass	M	$65kg$	Length between Joint 1 and Link1 CoM (m_1) in Link1 direction	lc_1	$0.10m$
Link1 mass	m_1	$10kg$	Link3 length	l_3	0.07m
Joint 1 range of motion	θ_1	0°~60°	Length between Joint 1 and Actuator1 mounting position in Link1 direction	lp_{1_a}	$0.166m$
Link1 length	l_1	$0.22m$	Actuator1 mounting position in vertical axis	$P1y_a$	$P1y$
Gas spring1 specification and installation condition					
Max. extension angle of Joint 1	θ_{1_max}	60°	Nominal initial force	Fs_{1_min}	$900N$
Max. length at resting position	ls_{1_full}	$190mm$	Max. stroke	Δls_1	$50mm$
Spring constant	Ks_1	$9N/mm$	Number of gas spring	n_{s1}	2
Formulas required to calculate the torque (T_{s1}) produced by Gas spring1					
Gas spring1 mounting position (P1) in vertical axis	$P1y$: calculated from optimization				
Length between Joint 1 and Gas spring1 mounting position (PP1)	$lp_1 = \frac{2 \cdot P1y \cdot \cos(\pi/2 + \theta_{1_max}) + \sqrt{(2 \cdot P1y \cdot \cos(\pi/2 + \theta_{1_max}))^2 - 4 \cdot (P1y^2 - ls_{1_full}{}^2)}}{2}$				
Gas spring1 length	$ls_1 = \sqrt{lp_1{}^2 + P1y^2 - 2 \cdot lp_1 \cdot P1y \cdot \cos(\pi/2 + \theta_1)}$				
Gas spring1 moment arm	$lm_1 = \frac{lp_1 \cdot P1y \cdot \sin(\pi/2 + \theta_1)}{ls_1}$				
(Total) Force by Gas spring1	$Fs_1 = \{-(ls_1 - ls_{1_full}) \cdot Ks_1 + Fs_{1_min}\} \times n_{s1}$				
Torque by Gas spring1	$T_{s1} = Fs_1 \cdot lm_1$				
Actuator1 specification and installation condition					
Max. force by Actuator1	Fa_{1_max}	± 3000N	Number of Actuator1 in parallel	n_{a1}	1
Max. stroke	Δla_1	$50mm$	-	-	-
Torques (T_{req1}, T_{mot1}) to fully compensate the gravity torque (T_{g1})					
Theoretical torque to compensate the gravity torque at Joint 1	$T_{req1} = -T_{g1} = (M \cdot g \cdot l_1 + m_1 \cdot g \cdot lc_1 + m_2 \cdot g \cdot l_1) \cdot \cos\theta_1$				
Motor torque to fully compensate the gravity torque	$T_{mot1} = T_{req1} - T_{s1}$				
Actuator1 Length	$la_1 = \sqrt{(lp_{1_a}{}^2 + P1y_a^2 - 2 \cdot lp_{1_a} \cdot P1y_a \cdot \cos(\pi/2 + \theta_1))}$				
Actuator1 moment arm	$lm_{a1} = \frac{lp_{1_a} \cdot P1y_a \cdot \sin(\pi/2 + \theta_1)}{la_1}$				
(Total) Actuator1 force to fully compensate the gravity torque	$Fa_1 = (T_{mot1}/lm_{a1})$				
(Total) Max. torque limit	$T_{mot3_max} = \pm(Fa_{1_max} \times n_{a1}) \cdot lm_{a1}$				

Table II. System parameters, component specifications and installation conditions, and torque formulas associated with Joint 2

Parameter values used in optimization					
Link2 mass	m_2	$22kg$	Length between Joint 2 and subject CoM (M) in Link2 direction	lcm_2	$0.24m$
Joint 2 range of motion	θ_2	$-35°\sim75°$	Length of perpendicular from subject CoM (M) to Link2	l_h	$0.01m$
Length between Joint 2 and Link2 CoM (m_2) in Link2 direction	lc_2	$0.15m$	Length of perpendicular from Joint 2 to Link2	h_{off}	$0.03m$
Gas spring2 specification and installation condition					
Max. extension angle of Joint 2	θ_{2_max}	75°	Nominal initial force	Fs_{2_min}	$900N$
Max. length at resting position	ls_{2_full}	$293mm$	Max. stroke	Δls_2	$100mm$
Spring constant	Ks_2	$4.5N/mm$	Number of gas spring	n_{s2}	2
Formulas required to calculate the torque (T_{s2}) produced by Gas spring2					
Gas spring2 mounting position(P2) in horizontal axis	$P2x$: calculated from optimization				
Gas spring2 mounting position(P2) in vertical axis	$P2y$: calculated from optimization				
Gas spring2 mounting position (P2) angle offset	$\theta_e = \tan^{-1}\frac{P2x}{P2y}$				
Subject CoM (M) angle offset relative to Link2	$\theta_h = \tan^{-1}\frac{l_h + h_{off}}{l_{cm2}}$				
Angle between Link2 and Gas spring2	$\theta_{s2} = \cos^{-1}\frac{lp_2 - l_e}{ls_2}$				
Length between Joint 2 and Gas spring2 mounting position (PP2)	$lp_2 = \downarrow$				
$lp_2 = \frac{2\cdot P2x\cdot\cos\theta_{2_max} - 2\cdot P2y\cdot\sin\theta_{2_max} + \sqrt{(2\cdot P2x\cdot\cos\theta_{2_max} - 2\cdot P2y\cdot\sin\theta_{2_max})^2 - 4\cdot(P2x^2 + P2y^2 + {h_{off}}^2 + 2\cdot P2y\cdot h_{off}\cdot\cos\theta_{2_max} + 2\cdot P2x\cdot h_{off}\cdot\sin\theta_{2_max} - {ls_{2_full}}^2)}}{2}$					
Gas spring2 length	$ls_2 = \sqrt{(lp_2\cdot\cos\theta_2 - P2x - h_{off}\cdot\sin\theta_2)^2 + (lp_2\cdot\sin\theta_2 + P2y + h_{off}\cdot\cos\theta_2)^2}$				
Length between Joint 2 and Gas spring2 mounting position (P2) in Link2 direction	$l_e = \sqrt{(P2x^2 + P2y^2)}\cdot\sin(\theta_e - \theta_2)$				
Gas spring2 moment arm	$lm_2 = lp_2\cdot\sin\theta_{s2} - h_{off}\cdot\sin(\pi/2 - \theta_{s2})$				
(Total) Force by Gas spring2	$Fs_2 = \{-(ls_2 - ls_{2_full})\cdot Ks_2 + Fs_{2_min}\}\times n_{s2}$				
(Total) Torque by Gas spring2	$T_{s2} = Fs_2\cdot lm_2$				
Actuator2 specification and installation condition					
Number of Actuator2 in parallel	n_{a2}	1	-	-	-
Torques (T_{req2}, T_{mot2}) to fully compensate the gravity torque (T_{g2})					
Theoretical torque to compensate the gravity torque at Joint 2	$T_{req2} = -T_{g2} = M\cdot g\sqrt{{lcm_2}^2 + (l_h + h_{off})^2}\cdot\cos(\theta_2 + \theta_h) + m_2\cdot g\cdot(lc_2\cdot\cos\theta_2 - h_{off}\cdot\sin\theta_2)$				
Motor torque to fully compensate the gravity torque	$T_{mot2} = T_{req2} - T_{s2}$				

Table III. System parameters, component specifications and installation conditions, and torque formulas associated with Joint 3

Parameter values used in optimization					
Loading mass	M_r	$52kg$	Length between Joint J_c and Gas spring3 mounting position (PP3) in Link6 direction	lp_3	$0.035m$
Tilt mass	M_t	$59kg$	Length between Joint J_c and Actuator3 mounting position in Link6 direction	lp_{3_a}	$0.375m$
Joint 3 range of motion	θ_3	0°~77°	Length of perpendicular from tilt mass (M_t) to Joint 3 in Link7 direction	ltt	$0.2m$
Loading mass (M_r) angle offset from vertical axis	θ_r	5°	Length of the slightly protruding part on Link5 and Link7	lz	$0.05m$
Joint 3 angle offset	θ_{off}	30°	Length of perpendicular from Gas spring3 mounting position (PP3) to Link6	hp_3	$0m$
Link2 length	l_2	$0.42m$	Length of perpendicular from Actuator3 mounting position to Link6	hp_{3_a}	$0m$
Length between Joint 3 and loading mass (M_r)	lc_r	$0.30m$	Actuator3 mounting position in horizontal axis	$P3x_a$	$0.375m$
Length between Joint 3 and Joint J_c	l_{off}	$0.10m$	Actuator3 mounting position in vertical axis	$P3y_a$	$0m$
Gas spring3 specification and installation condition					
Max. extension angle of Joint 3	θ_{3_max}	77°	Nominal initial force	Fs_{3_min}	$400N$
Max. length at resting position	ls_{3_full}	$393mm$	Max. stroke	Δls_3	$150mm$
Spring constant	Ks_3	$1.33N/mm$	Number of gas spring	n_{s3}	2
Formulas required to calculate the torque (T_{s3}) produced by Gas spring3					
Gas spring3 mounting position (P3) in horizontal axis	$P3x$: calculated from optimization				
Gas spring3 mounting position (P3) in vertical axis	$P3y$: calculated from optimization				
Angle between Link6 and Gas spring3	$\theta_{s3} = abs\{\tan^{-1}\frac{-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_3+P3y}{(l_{off}\cdot\sin(\theta_{off}-\theta_3)+l_2-lp_3)-P3x}\}$				
Gas spring3 length	$ls_3 = \sqrt{((l_{off}\cdot\sin(\theta_{off}-\theta_3)+l_2-lp_3)-P3x)^2+(-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_3+P3y)^2}$				
Gas spring3 moment arm	$lm_3 = \text{abs}\{-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_3+P3y\}\cdot\cos\theta_{s3}+\{lp_3-l_{off}\cdot\sin(\theta_{off}-\theta_3)\}\cdot\sin\theta_{s3}+P3y\cdot\cos\theta_{s3}$				
(Total) Force by Gas spring3	$Fs_3 = \{-(ls_3-ls_{3_full})\cdot Ks_3+Fs_{3_min}\}\times n_{s3}$				
(Total) Torque by Gas spring3	$T_{s3} = -Fs_3\cdot lm_3$				
Actuator3 specification and installation condition					
Max. force by Actuator3	Fa_{3_max}	±1000N	Number of Actuator 3 in parallel	n_{a3}	2
Max. stroke	Δla_3	$150mm$	-	-	-
Torques (T_{req3}, T_{mot3}) to fully compensate the gravity torque (T_{g3})					
Theoretical torque to compensate the gravity torque at Joint 2	$T_{req3} = -T_{g3} = -M_r g lc_r\sin(\theta_3+\theta_r)$				
Motor torque to fully compensate the gravity torque	$T_{mot3} = T_{req3} - T_{s3}$				
Angle between Link6 and Actuator3	$\theta_{a3} = abs\{\tan^{-1}\frac{-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_{3_a}+P3y_a}{lp_{3_a}+P3x_a-l_{off}\cdot\sin(\theta_{off}-\theta_3)-l_2}\}$				
Actuator 3 length	$la_3 = \sqrt{(lp_{3_a}+P3x_a-l_{off}\cdot\sin(\theta_{off}-\theta_3)-l_2)^2+(-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_{3_a}+P3y_a)^2}$				
Actuator 3 moment arm	$lm_{a3} = \text{abs}\{(-l_{off}\cdot\cos(\theta_{off}-\theta_3)+hp_{3_a}+P3y_a)\}\cdot\cos\theta_{a3}+(l_{off}\cdot\sin(\theta_{off}-\theta_3)+l_2-lp_{3_a})\cdot\sin\theta_{a3}+P3y_a\cdot\cos\theta_{a3}$				
(Total) Actuator1 force to fully compensate the gravity torque	$Fa_3 = (T_{mot3}/lm_{a3})$				
(Total) Max. torque limit	$T_{mot3_max} = \pm(Fa_{3_max}\times n_{a3})\cdot lm_{a3}$				
Torque to fully compensate the tilting torque at Joint 3	$T_{req3_tilt} = -M_t\cdot g\cdot(ltt\cdot\sin\theta_2+lz\cdot\cos\theta_2)$				

Table IV. Optimization parameters, objective function, and constraints

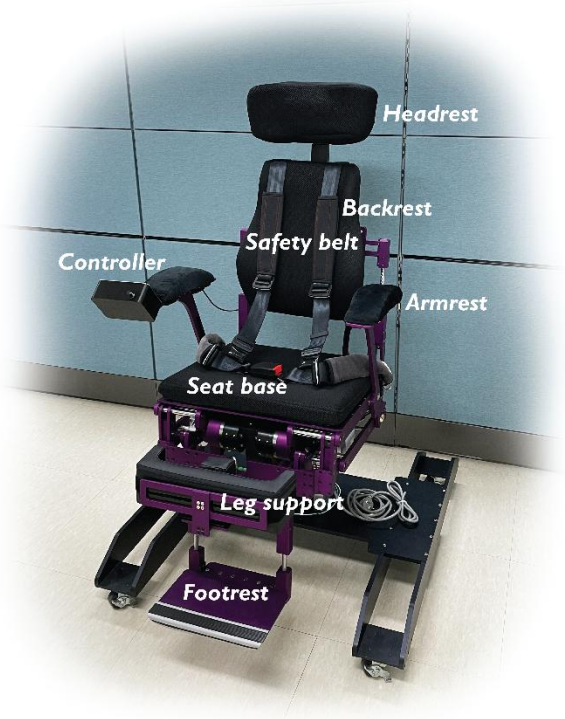
Optimization setup			
Optimization parameters for gas spring mounting positions with lower and upper bounds	Joint 1	P1y	$20mm$~$100mm$
	Joint 2	P2x	$20mm$~$100mm$
		P2y	$20mm$~$100mm$
	Joint 3	P3x	$50mm$~$100mm$
		P3y	$0mm$~$50mm$
Objective Function	F_{obj}		$TCE_{avg} = \frac{1}{N}\sum_{1}^{N}\{\lvert T_{req} - T_s \rvert\}$ *where N is number of data points through the range of motion*
Constraints	Joint 1	Gas spring stroke	$\Delta ls_1 \leq 50mm$
	Joint 2	Gas spring stroke	$\Delta ls_2 \leq 100mm$
	Joint 3	Gas spring stroke	$\Delta ls_3 \leq 150mm$
		Actuator max. force	$abs(Fa_3) \leq 1000N$

Table V. Types of postural transitions and corresponding joint angles

Posture	Joint 1	Joint 2	Joint 3
Default seating	4°	−4°	4°
Lifting	52°	−4°	4°
Forward leaning	20°	25°	25°
Tilting	50°	−37°	4°
Standing	32°	60°	62°
Reclining	0°	0°	66°

FIG. 1. Photographs of the modular postural transition device: (a) front view and components, (b) side view and range of motion of each joint.

(a)



(b)

FIG. 2. The fundamental structure of the postural transition device utilizing a double-parallelogram mechanism. The parallelogram structures of the upper and lower sections can overlap with each other, and the lower fastening part has a small area (125 mm x 125 mm) to facilitate easy attachment and detachment with various mobile bodies and supports.

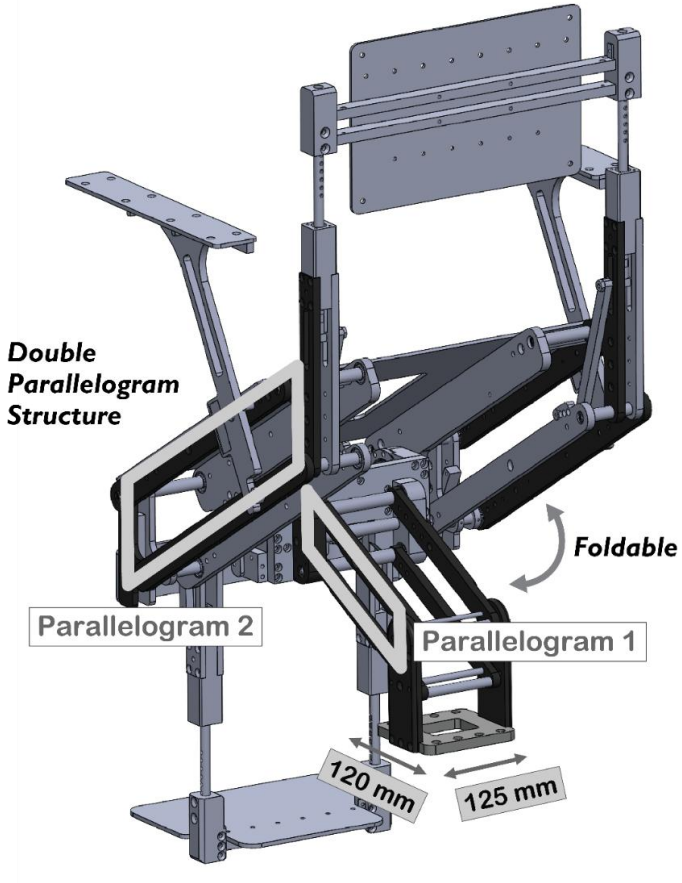


FIG. 3. A slider-crank mechanism synchronized with the parallelogram movement during postural transitions. This mechanism passively helps the backrest and footrest rise or lower with the postural changes, thereby alleviating pressure concentration and frictional wear at specific points caused by joint misalignment between the human body and the device. During postural transitions, the backrest and footrest can move up to 60 mm and 95 mm, respectively, with their initial positions adjustable in six stages, ranging from 10 mm to a maximum of 60 mm.

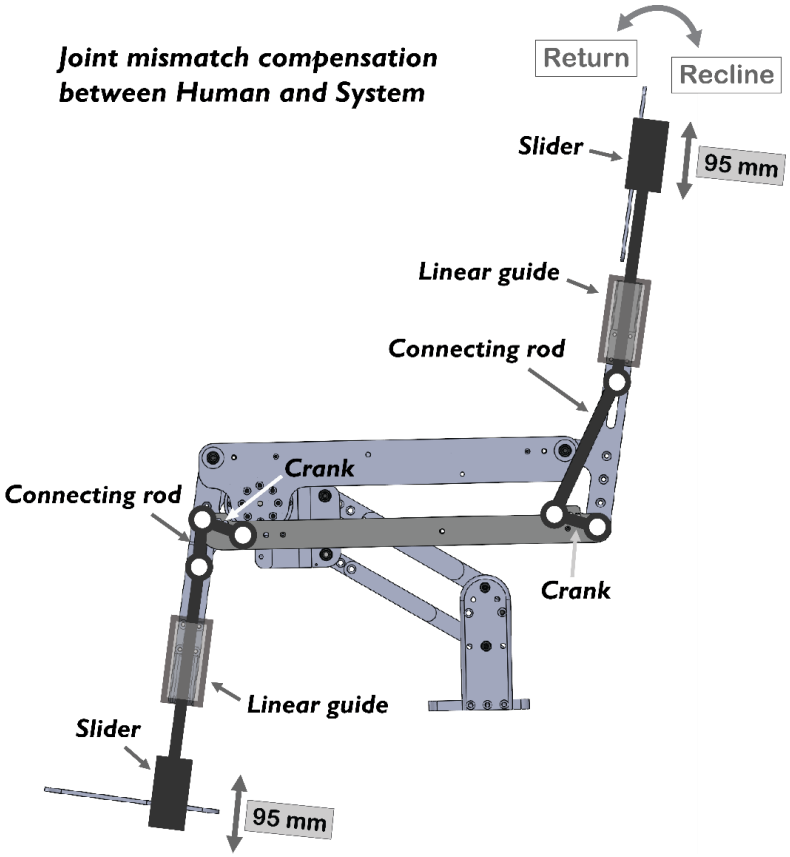


FIG. 4. An armrest synchronized with the parallelogram movement during postural transitions. It is connected to the upper and lower links of the parallelogram structure, with the upper link using a rotational joint and the lower link attached with a magnet. During postural transitions, the armrest maintains a constant angle with the backrest, and the user can detach the lower part of the armrest from the magnetic attachment point to tilt it backward when needed.

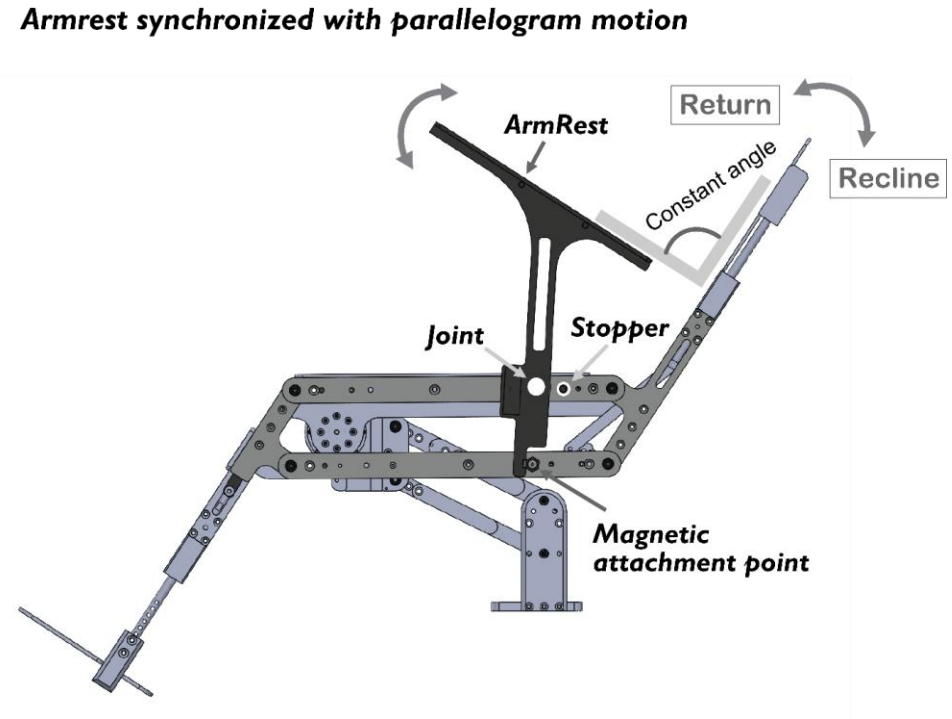


FIG. 5 Schematic drawings and free-body diagrams of (a, b) the lifting section, (c, d) the seat section, and (e, f) the backrest and footrest sections (represented by thick black solid links). The model parameters, including mass (m_1, m_2) and length (l_1, l_2), are presented alongside joint angle and joint torque, where the subscript indicates the corresponding joint number. For simplicity, all individual links are assumed to be massless. The gas spring installation locations for gravity compensation (P1, P2, P3) are determined through an optimization process. Detailed information on the model parameters, component specifications, installation conditions, and torque formulas is provided in Tables I, II, and III.

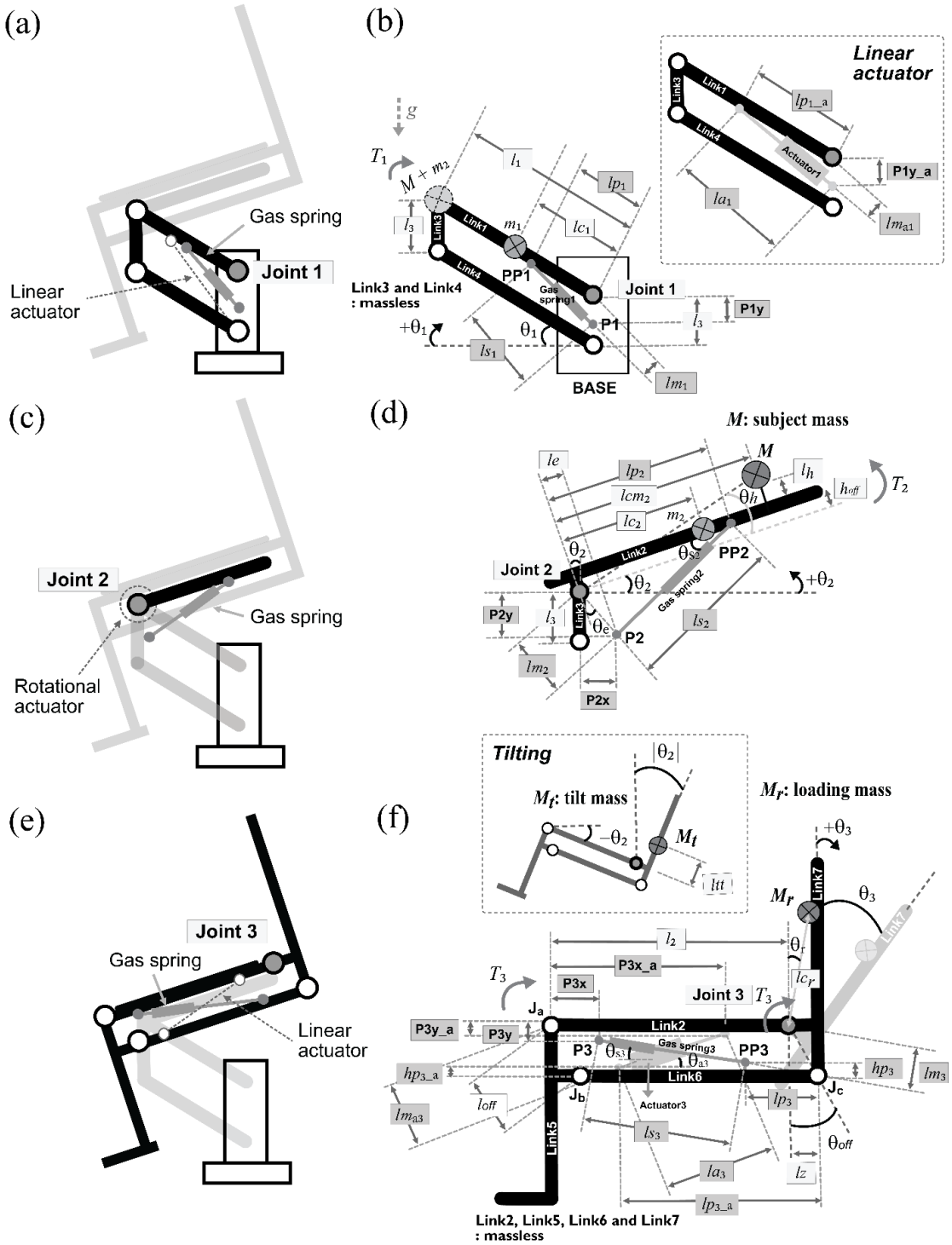


FIG. 6. Gravity compensation results: (a, b, c) Theoretical torques (T_{req}) for compensating gravity, torques (T_s) produced by the gas springs, and torques (T_{mot}) required to fully compensate the remaining gravitational torque, which is the difference between T_{req} and T_s at each joint. (d) Actuator forces (F_{mot}) needed to generate the corresponding torques (T_{mot}) for forward leaning and tilting are presented, along with the maximum force limit of the linear actuator, under the assumption that joint 3 remains backdrivable during the movements.

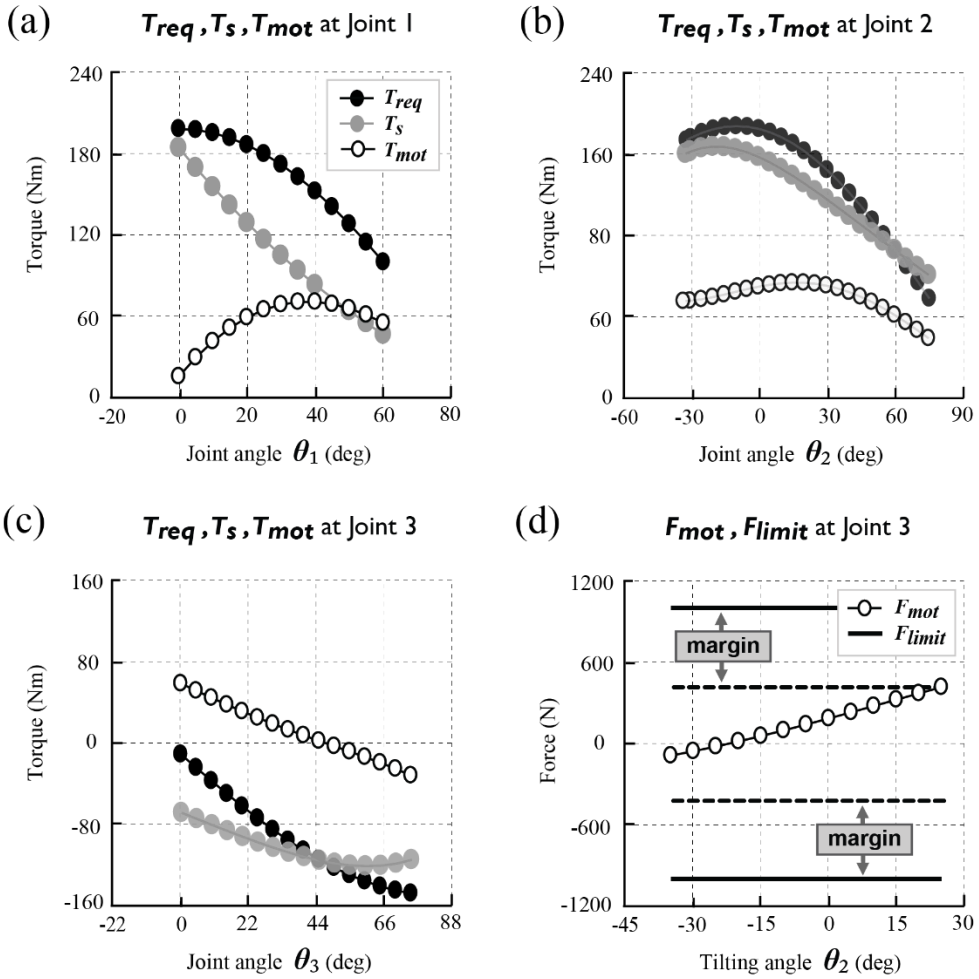


FIG. 7. Appearance of the control panel for the postural transition device and its operation when a button is pressed. The control panel consists of seven buttons, each corresponding to the following postures: (a) Basic seating, (b) Lifting, (c) Lowering, (d) Forward leaning, (e) Tilting, (f) Standing, and (g) Reclining. Among these, the (b) Lifting and (c) Lowering buttons allow for elevation and descent while maintaining the current posture. When a button is pressed, its light illuminates, and the postural transition speed can be adjusted using the rotary knob located at the top.

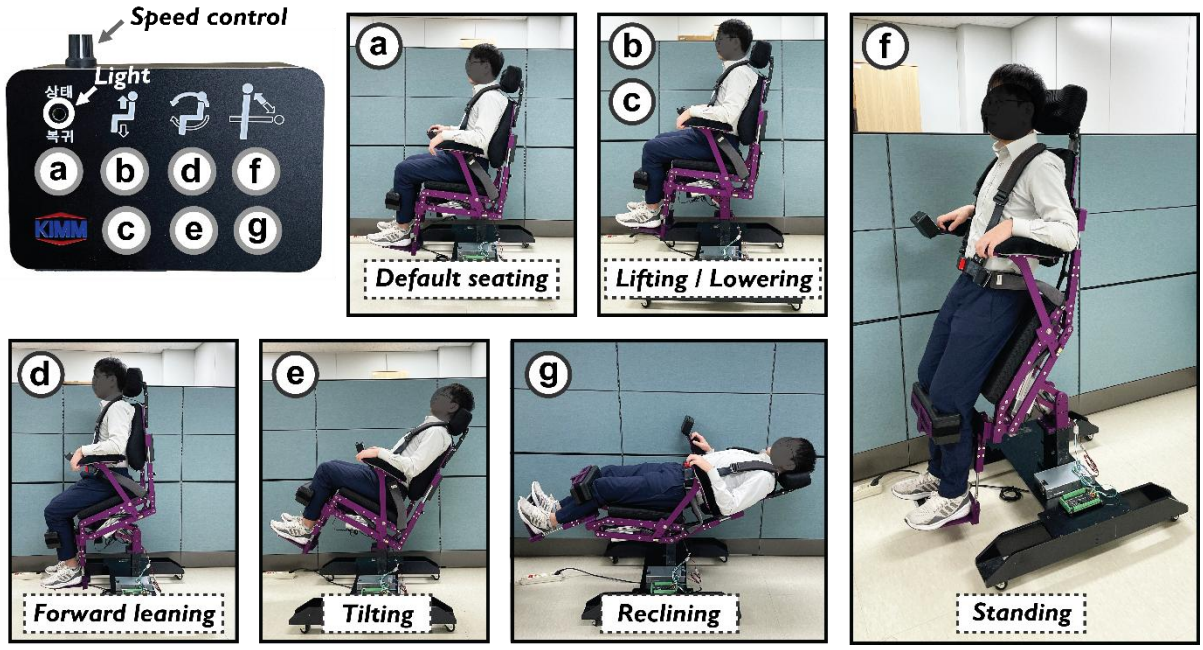


FIG. 8. (a) Definition of joint angles and their trajectories during posture transition and return processes: (b) lifting, (c) forward leaning, (d) tilting, (e) standing, and (f) reclining.

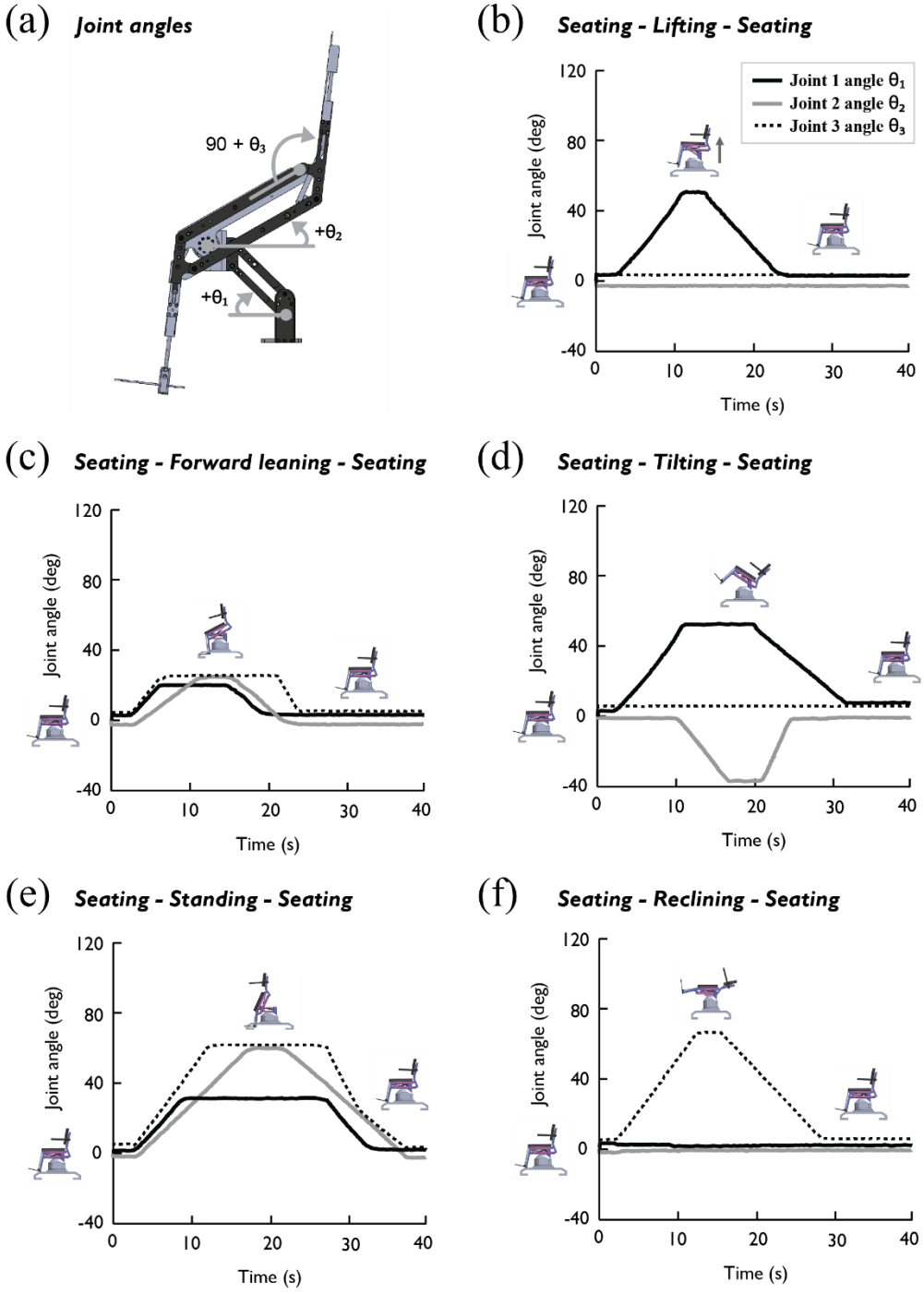


FIG. 9. (a) Load application on the seat and backrest of the modular postural transition device, with power graphs recorded during the posture transition and return processes under applied loads (by the subject): (b) Lifting, (c) Forward leaning, (d) Tilting, (e) Standing, and (f) Reclining.

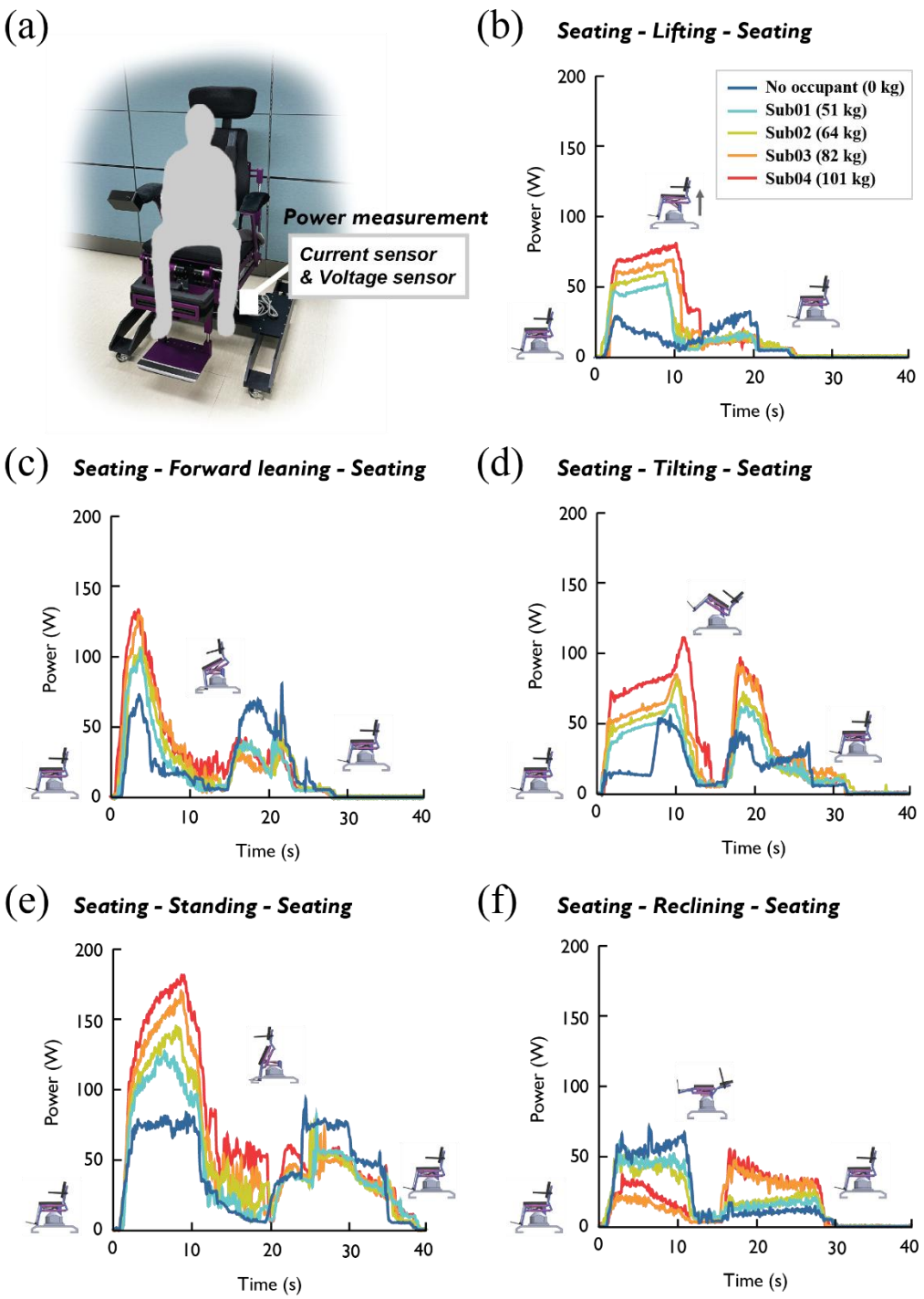
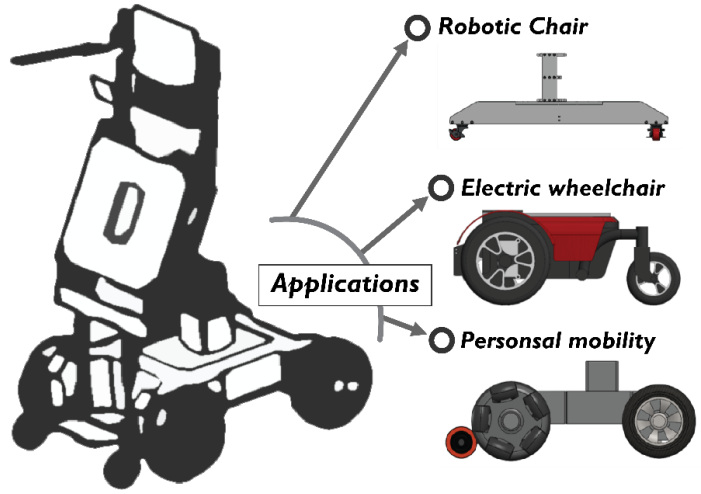



FIG. 10. Example applications of the postural transition device: It can be integrated with various mobility platforms (e.g., electric wheelchairs, personal mobility devices) or support structures (e.g., chair base frames).