Effects of an Electric Drive Wheel on Hand Forces, Muscle Activity, Spinal Load, and Usability During Hospital Bed Transport by Nursing Staff

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[1] Abbreviations: MSDs, musculoskeletal disorders; L5/S1, lumbar vertebra 5/sacral vertebra 1; EMG, electromyography; MVIC, maximum voluntary isometric contraction; DA, deltoideus anterior; TPD, trapezius pars descendens; ES, erector spinae; SUS, System Usability Scale; SD, standard deviation.

Abstract

This study investigated a novel motorized drive wheel designed to replace one of the four outer castors of a hospital bed. Existing beds can be retrofitted using a plug-and-play approach, offering considerable potential to reduce the physical burden on healthcare workers during bed transport. Thirteen nurses moved a standardized hospital bed—with and without the drive wheel—through a realistic course including ramps, curves, and elevators. Objective biomechanical parameters (hand forces, spinal compression, muscle activity) and subjective assessments (Borg scale, System Usability Scale) were recorded. The drive wheel significantly reduced physical load, lowering hand forces by 22% and spinal compression by 20%. Shoulder, neck, and lower-back muscle activity also decreased significantly. Perceived exertion was reduced by 69%, and usability was rated as “excellent.” Motorized drive wheels can substantially reduce physical strain in everyday clinical care, although recommended ergonomic limits were not met in all situations.

Keywords: Workload reduction, Hospital bed mobility, Spinal load

1. Introduction

Compared to other occupational groups, nursing staff exhibit an above-average prevalence of musculoskeletal disorders (MSDs). Among these, back pain is the most common, with a 12-month prevalence rate of 55%, followed by shoulder pain (44%) and neck pain (42%) (Davis and Kotowski, 2015). Pushing hospital beds is a routine task for many nurses (Poole Wilson et al., 2015). During patient transfers between wards or to diagnostic and treatment units, the musculoskeletal system is subjected to considerable strain, primarily due to the distances to be covered and the substantial weight of hospital beds. Overall, moving hospital beds is one of the most physically demanding activities in everyday nursing practice (Ando et al., 2000; Zhou and Wiggermann, 2017).

To date, few studies have investigated the physical strain involved in the movement of hospital beds. In a previous study, Leban et al. (2022) measured the hand forces exerted during pushing and pulling tasks. Twenty participants (11 men and 9 women) moved a hospital bed weighing 181 kg along a predefined test course in a hospital setting. One-dimensional force sensors recorded mean peak forces of 222 ± 49 N and 36 ± 16 N in the longitudinal (x) and transverse (z) directions, respectively.

Brütting et al. (2017) investigated musculoskeletal loads during the pushing and pulling of hospital beds and wheelchairs. Ten participants moved a hospital bed with varying loads across two test courses. Hand forces were measured using three-dimensional force handles, and body posture was recorded using a motion analysis system. Based on these data, the authors calculated the compression force between the fifth lumbar vertebra and first sacral vertebra (L5/S1). Maximum hand forces up to 368 N and spinal compression forces up to 3.7 kN were observed.

Moving hospital beds often exceeds recommended spinal compression limits. The German Social Accident Insurance Institution for the Health and Welfare Services therefore advises moving beds with two persons or using technical aids such as bed movers (Berufsgenossenschaft für Gesundheitsdienst und Wohlfahrtspflege, 2023).

Bed movers are motorized devices designed to couple with hospital beds, providing mechanical assistance to nursing staff during patient transport. For example, Daniell et al. (2014) and Guo et al. (2017) showed that their use significantly reduced muscular strain during bed movement. However, bed movers are not commonly used in hospitals. Barriers to implementation include high acquisition costs, sometimes bulky design that complicates use in patient rooms and elevators, and the additional time required to locate, retrieve, and attach or detach the devices.

Integrating drive systems into hospital beds can address these limitations. Electrically powered fifth wheels, centrally mounted beneath the bed, provide driving, braking, and inclination assistance. Matz and Morgan (2018) showed that the “IndiGo” system (Arjo) reduced muscular effort for bed movement by 72% in various scenarios. Wiggermann (2017) reported that a powered fifth wheel (Hill-Rom) reduced peak forces by 38% when entering elevators and by 94% on ramps.

Electrically powered fifth wheels are currently available only for specific models from particular manufacturers and are, therefore, rarely used in hospitals. Moreover, these systems often compromise the under-bed clearance required for mobile patient lifts—an essential aid for reducing musculoskeletal strain during patient transfers and mobilization (Kong et al., 2023).

Against this background, the companies TENTE (TENTE-ROLLEN GmbH, Wermelskirchen, Germany) and LINAK (LINAK A/S, Nordborg, Denmark) have developed the electrically powered wheel “WeAssist.” This system can be mounted on existing hospital beds using a plug-and-play approach, without the need for special tools.

Fig. 1 shows the wheel and battery unit installed beneath the bed. Unlike previous systems, this wheel is not mounted as a fifth wheel but replaces one of the four outer wheels. This design allows for the retrofitting of even older hospital beds, offering the potential to significantly reduce the physical workload of many nurses in daily practice.

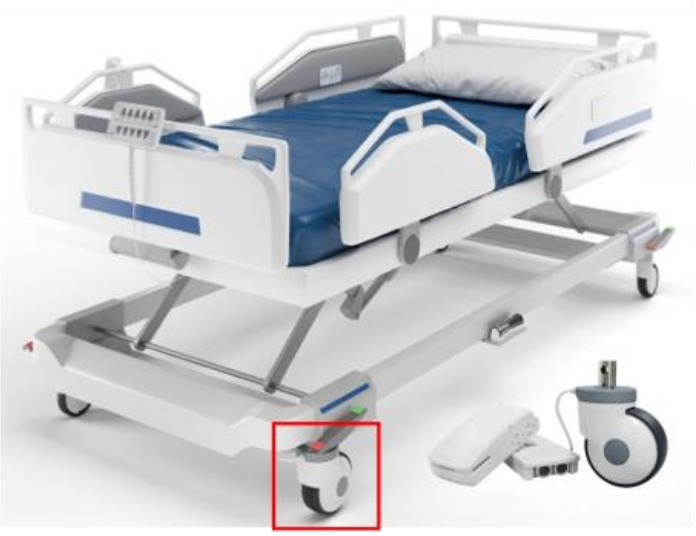


Fig. 1. Retrofit-capable electric wheel "WeAssist," developed by TENTE and LINAK, with battery unit mounted on a hospital bed

Sensors integrated into the wheel detect when the caregiver is pushing, braking, or navigating in an inclined or declined manner, such as on ramps. The built-in software interprets these movements and automatically activates an electric motor housed within the wheel casing, thereby providing assistance during pushing or braking. Unlike previous motorized systems, no throttles or switches are required; caregivers operate the bed as usual, with motor assistance automatically adjusted to the situation.

This study aimed to examine the extent to which the motorized wheel reduces physical strain during bed transport. The investigation included an assessment of objective biomechanical parameters—such as exerted force and spinal and muscular load—as well as subjective evaluations by nursing staff regarding perceived strain and usability.

2. Material and methods

2.1 Sample and Experimental Design

Thirteen nursing professionals (five males and eight females) participated in the study. The average age was 31 ± 5 years, with a mean body weight of 77 ± 16 kg and an average height of 172 ± 10 cm. They had 10 ± 6 years of professional experience. Ten moved hospital beds daily, and three did so weekly. None reported musculoskeletal complaints. All wore their usual work shoes, provided informed consent, and received compensation for their participation.

The tests were conducted using a hospital bed (S 962-2, Völker GmbH, Witten, Germany), which weighed 143 kg and measured 220 cm × 90 cm. An additional load of 107 kg, including a patient manikin, force measurement handles, a laptop, and weights, was added. This load corresponds to the 90th percentile of body weight for men aged 60–69 years in Germany (Fischer et al., 2020). Including the mattress weight (9.8 kg), the total weight amounted to 259.8 kg.

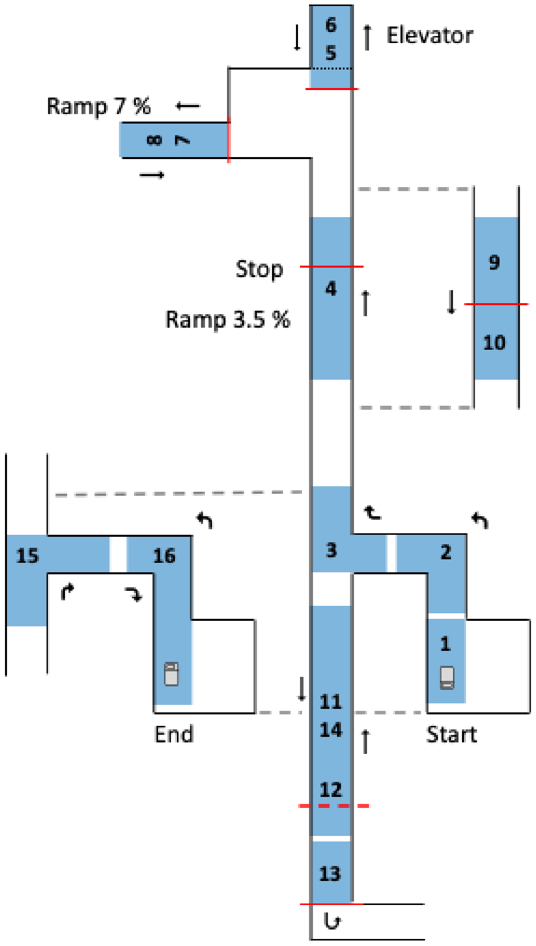
To examine the impact of the electric wheel on physical strain, nursing staff moved the same hospital bed both without assistance and with the electric drive wheel mounted on the front left caster of the bed.

2.2 Procedure

Measurements were conducted in the service area of a German hospital. The 240 m test course (Fig. 2) included three 90° right turns, one 90° left turn, an elevator, a 17 m ramp with a 3.5% incline, and a 12 m ramp with a 7% incline. Except for the 7% ramp, the floor was tiled. The 7% ramp served as the entrance to a ward and was covered with hospital-grade linoleum.

Fig. 2 shows the specific 16 intervals of the test course that were analyzed. Intervals 1 and 13 (*Pushing start phase flat surface*), 3 and 15 (*Right turn*), and 11 and 14 *(Rolling phase long corridor*) were collectively analyzed.

Before several intervals, participants were instructed to bring the bed to a complete stop to measure deceleration forces (intervals 4, 12, and 16). In subsequent intervals, acceleration from a standstill was measured (intervals 1, 5, 6, 7, and 10). These stop points are indicated in red in Fig. 2. The stop before the 7% ramp was on a flat surface directly before the incline. For the 3.5% ramp, the stop occurred on the ramp itself.



1 Pushing start phase flat surface
2 Left turn
3 Right turn
4 Push down and stop negative ramp -3,5%
5 Elevator entry
6 Elevator exit (pull)
7 Push up ramp +7 %
8 Push down ramp -7 %
9 Push up and stop ramp +3.5%
10 Pushing start phase positive ramp +3.5%
11 Rolling phase long corridor
12 Unplanned stop
13 Pushing start phase flat surface
14 Rolling phase long corridor
15 Right turn
16 Right turn and stop

Fig. 2. Schematic representation of the test course, showing the chronological sequence of analyzed intervals (1–16). Red markers indicate defined stop points where the bed was brought to a complete halt and subsequently accelerated from a standstill

Each participant completed the course three times, with and without the motorized wheel. The starting configuration was randomized. Prior to the test runs, all participants performed a trial run under both configurations (manual and motorized) to familiarize themselves with the course and handling of the bed.

In each movement condition, two unplanned stops were introduced during the rolling phase along a long corridor (intervals 11 and 13), triggered by a signal from the test supervisor.

After completing each condition, participants filled out questionnaires assessing subjective strain using the Borg CR10 scale and user acceptance using the System Usability Scale (SUS) (see Section 2.3.4).

2.3 Measures

2.3.1 Exerted Forces

To determine the forces exerted by nursing staff when moving the hospital bed with and without the motorized wheel, three-dimensional force handles (Type 9809A, Kistler Instrumente AG, Switzerland) were used.

The force handles were mounted on the hospital bed using a custom-built adapter (Fig. 3). Their height was individually adjusted to match the body dimensions of each participant, corresponding to the midpoint between the wrist and elbow when standing upright with arms extended downward (Brütting et al., 2017). This ensured standardized force application while accounting for individual anthropometric differences (Looze et al., 2000).

Both the direction and magnitude of the exerted force were calculated using the three force components in the local coordinate system. The measurement frequency was set to 50 Hz. Two cameras recorded the test procedure: one mounted at the foot of the bed and the other at the head, facing the participant.

Fig. 3. Mounting of force handles on the hospital bed. The handles comprised a plastic grip, which was connected on both sides to three-dimensionally measuring piezoelectric force sensors housed in an aluminum casing containing the amplifier electronics.

For each interval, mean and maximum forces were calculated for both bed configurations. First, the three trials were averaged per participant. Then, overall mean and maximum values, including standard deviations (SD), were derived from the participant-level averages.

Measured mean and maximum forces were compared to the thresholds defined in EN 60601-2-52:2016-04, which specify 160 N for the initial push and 85 N for maintaining motion.

2.3.2 Spinal Compression Force at L5/S1

For the biomechanical analysis, the validated and established model "Der Dortmunder" was used. This model represents a 30-segment musculoskeletal system with 24 joints and calculates compressive and shear forces, as well as flexion and torsional moments at the L5/S1 lumbar intervertebral disc, based on body posture, exerted forces, and anthropometric data (Ditchen et al., 2015; Jäger et al., 2001).

For the quantitative assessment of body posture, a motion analysis system (Xsens MVN Awinda; Movella Inc., USA) was employed. The system's sensors were affixed to the relevant body segments of the participants using elastic Velcro straps and medical adhesive tape.

The calculations were performed using WIDAAN software developed by the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA). This software enables the synchronized recording and analysis of exerted forces and body postures. To ensure data comparability, spinal compression forces were calculated for a standardized reference individual (175 cm, 75 kg).

The maximum and mean spinal compression forces (± SDs) were calculated using the same procedure as for the exerted forces and analyzed separately for each interval. Results were compared with the revised "Dortmund Threshold Values," which recommend maximum lumbar spine loads during manual handling based on sex and age. For women aged 50–60 years, the limit is 2.2 kN; for those over 60 years, 1.8 kN (Jäger, 2019).

2.3.3 Muscular Strain

To assess muscular strain during hospital bed movement, the activities of the *Musculus* (M.) deltoideus anterior (DA), M. trapezius pars descendens (TPD), and M. erector spinae (ES) were measured bilaterally using surface electromyography (sEMG) sensors. Electrode placement followed the SENIAM recommendations (Hermens et al., 1999). The WavePlus system was used in combination with wireless Pico sensors (Cometa Srl, Italy) at a sampling rate of 2000 Hz. Motion artifacts and high-frequency noise were reduced using a 2–200 Hz band-pass filter. Data were smoothed with a 100 ms root mean square window and processed with a 3 Hz low-pass filter to generate a linear envelope. Before electrode placement (Kendal H93SG, Cardinal Health, USA), body hair was removed and the skin prepared with abrasive paste and alcohol.

Maximum voluntary isometric contraction (MVIC) was recorded as a reference for signal normalization. The following exercises were performed to measure MVIC:

- **M. DA**: standing arm abduction at 45° in the sagittal plane against static resistance.
- **M. TPD**: bilateral shoulders shrugged while holding the rear end of the hospital bed.
- **M. ES**: Biering–Sørensen test (Vinstrup et al., 2017): performed in a prone position with the trunk extended, upper body unsupported, and legs stabilized.

For analysis, each measurement within an interval was averaged to calculate the mean muscle activity per participant. Subsequently, the overall mean and SD for each interval were calculated across all participants.

2.3.4 Perceived Strain and User Satisfaction

In addition to objective measurements, perceived exertion among participants was assessed using the Borg CR10 scale, a validated instrument for evaluating physical effort (Borg, 1998). The scale ranged from 0 (“no exertion at all”) to 10 (“very, very high effort, nearly maximal”).

User satisfaction for both movement types (manual and assisted) was assessed using the SUS, which consists of ten standardized statements rated on a five-point Likert scale. SUS scores, ranging from 0 to 100, provide a comparative measure of usability. According to Bangor et al.(2009), these scores can be interpreted as follows:

- **>80.3**: Excellent usability
- **68–80.3**: Good to acceptable usability
- **50–68**: Adequate usability, but in need of improvement
- **<50**: Poor usability

For analysis, the Borg CR10 and SUS values were averaged across all participants for each bed configuration. Standard deviations were calculated to assess the variability of responses.

2.4 Statistical Analysis

Maximum and mean values of exerted forces, spinal compression forces, and EMG measurements were tested for normality using the Shapiro–Wilk test (significance level: $\alpha = .05$). If normality was confirmed, a paired-samples *t*-test was conducted; otherwise, the non-parametric Wilcoxon signed-rank test was applied ($\alpha = .05$). For perceived exertion and user acceptance, only the Wilcoxon signed-rank test was used. The analyses aimed to determine statistically significant differences between the two test conditions: “manual pushing” versus “assisted pushing.”

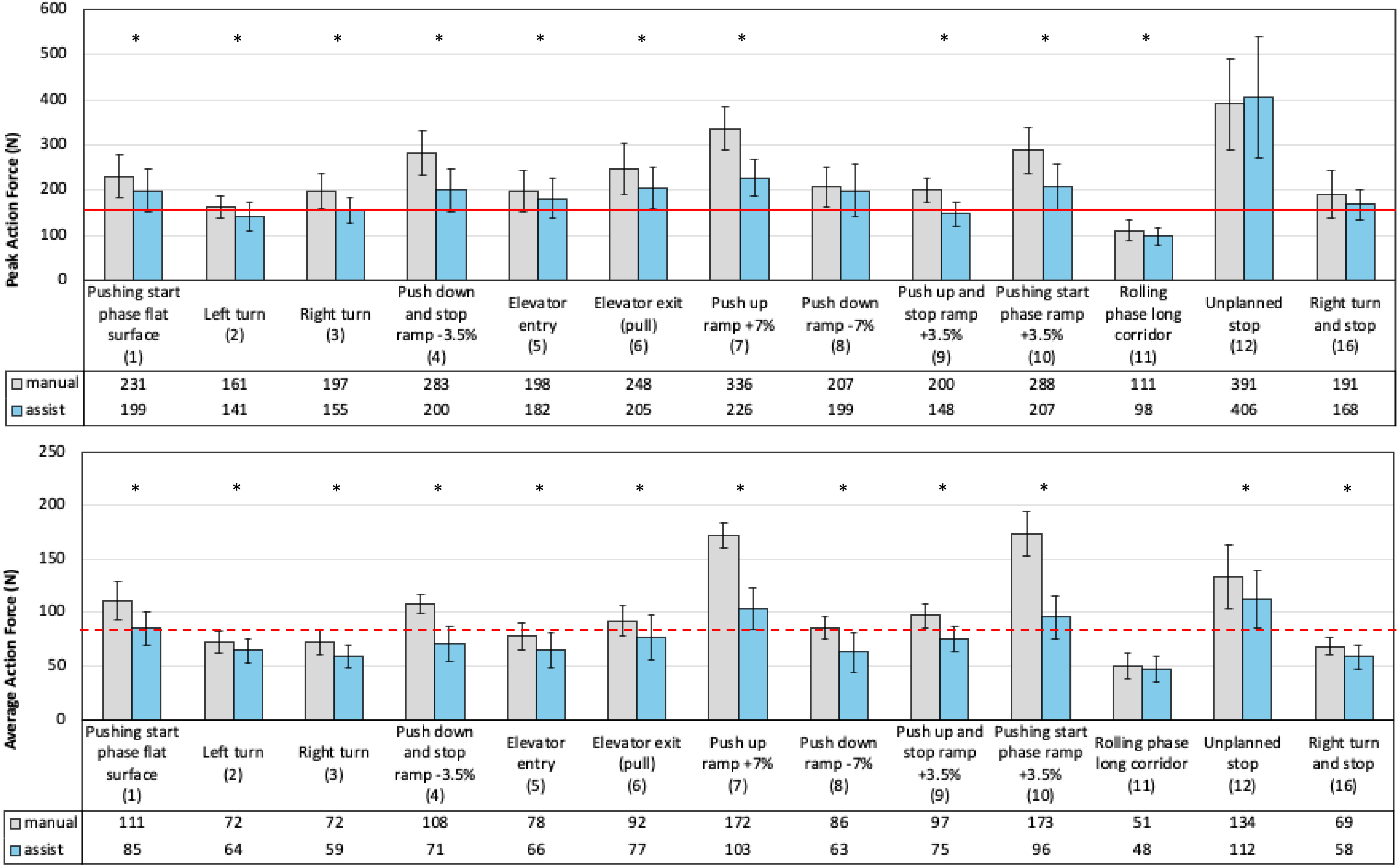
3. Results

3.1 Exerted Forces

Fig. 4 shows the average maximum and mean exerted forces across all participants, segmented by the test course intervals, with maximum values shown in the upper and mean values in the lower graph. Except for *Unplanned Stop*, *Push down ramp −7%*, and *Right turn and stop*, the motorized wheel significantly reduced **maximum forces** in 10 of 13 intervals ($p < .05$). The largest reductions occurred on ramps: −33% on *ramp +7%*, −28% on *ramp +3.5%*, and −29% when descending and stopping on *ramp −3.5%*. No significant change was observed on *ramp −7%*. Reductions in turns were −22% (*Right turn*) and −12% (*Left turn*). Averaged across all intervals, maximum forces decreased by 16%.

Mean forces were significantly reduced in all intervals except *Rolling phase* ($p < .05$), with the largest decreases again on ramps (−40% on *ramp +7%*, −45% on *ramp +3.5%* start phase). On level ground (*Start phase level*), the reduction was −23%. In turns, reductions were −18% (right) and −11% (left). Across all intervals, mean forces decreased by 22%.

In all five acceleration intervals (1, 5, 6, 7, 10), the 160 N threshold from EN 60601-2-52:2016-04 was exceeded during both manual pushing and motorized assistance. The 85 N limit for maintaining motion was exceeded in 8 of 13 intervals manually, but only in 3 with assistance.



	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
☐ manual	231	161	197	283	198	248	336	207	200	288	111	391	191
☐ assist	199	141	155	200	182	205	226	199	148	207	98	406	168

	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
☐ manual	111	72	72	108	78	92	172	86	97	173	51	134	69
☐ assist	85	64	59	71	66	77	103	63	75	96	48	112	58

Fig. 4. Comparison of averaged maximum (top) and mean forces (bottom) across the interval segments. Gray bars indicate manual pushing; blue bars indicate motorized assistance. * indicates significant differences ($p < .05$). Red lines indicate threshold values based on EN 60601-2-52:2016-04; solid line: 160 N (acceleration phase); dashed line: 85 N (maintaining motion)

3.2 Spinal Compression Force at L5/S1

Fig. 5 shows the maximum and mean spinal compression forces (L5/S1) during hospital bed movement with and without motorized assistance. Without assistance, **maximum compression forces** ranged from 1.8 kN (*Rolling phase*) to 4.1 kN (*Push up ramp +7%*). With motorized assistance, the values ranged from 1.7 kN to 2.8 kN.

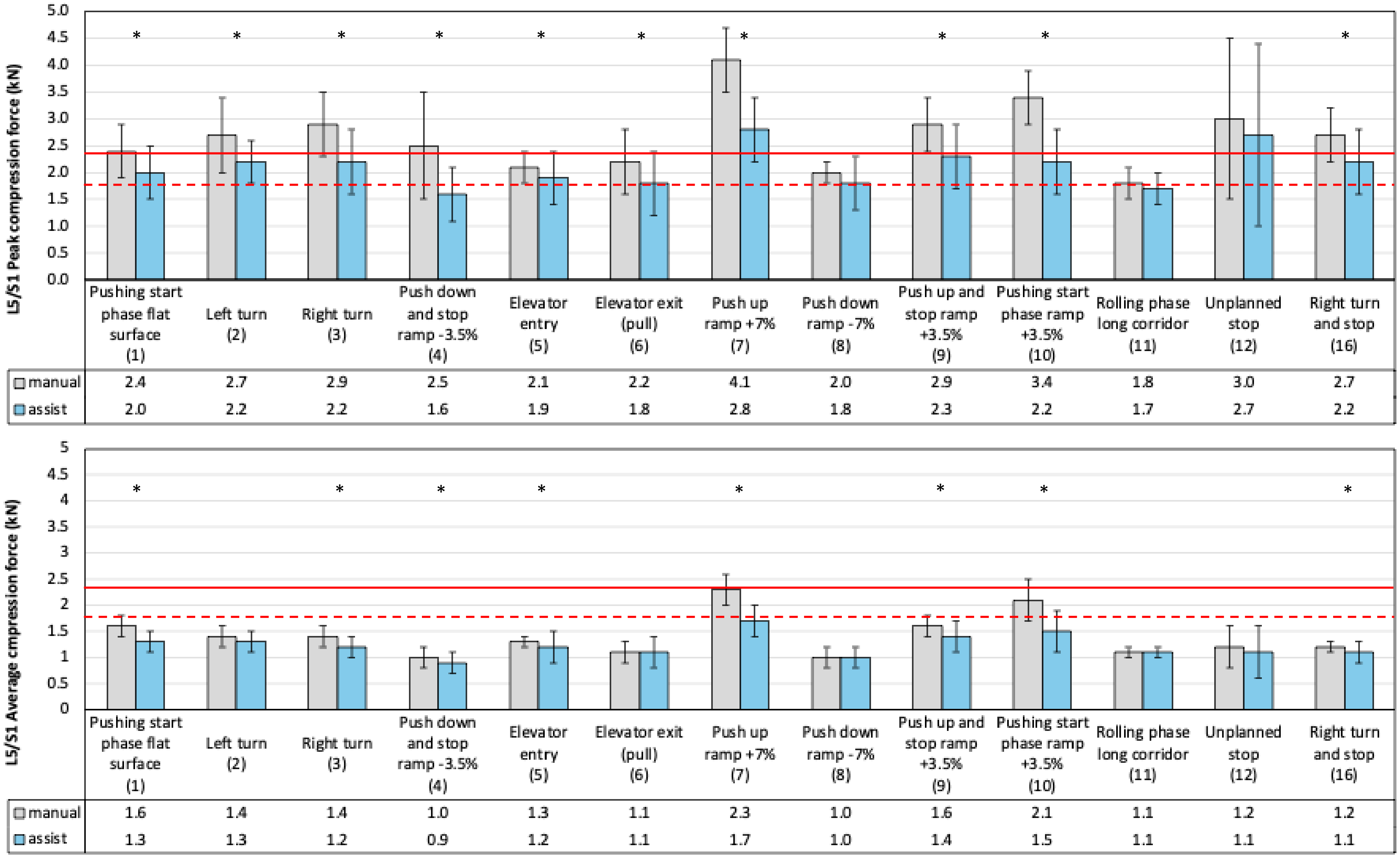
In 10 of 13 intervals, the motorized wheel significantly reduced maximum compression forces (*p* < .05). As observed with exerted forces, the greatest reductions occurred in the ramp intervals. When pushing up the 7% ramp, the maximum compression force decreased from 4.1 kN to 2.8 kN (−32%); during the start phase on the 3.5% ramp, it dropped from 3.4 kN to 2.2 kN (−35%). In right turns, the maximum compression force decreased by 24%, whereas in left turns by 19%. Across all intervals, motorized assistance resulted in an average reduction of 20% in maximum spinal compression forces.

The lower graph in Fig. 5 shows the **mean spinal compression forces** averaged across all participants. These ranged from 0.9 kN (*Push down and stop ramp −3.5%* with assistance) to 2.3 kN (*Push up extreme ramp 7%* without assistance).

In 8 of 13 intervals, motorized assistance significantly reduced mean spinal compression forces (*p* < .05). As with the maximum compression forces, the greatest reductions in mean compression forces were observed in the ramp intervals. When pushing up the 7% ramp, the mean compression force decreased by 26% with motorized assistance; during the start phase on the 3.5% ramp, it decreased by 29%. On level ground, the mean compression force during bed acceleration was reduced by 19%. In right turns, a 14% reduction was observed. Across all intervals, motorized assistance resulted in an average reduction of 11% in mean spinal compression forces.

Compared with the Dortmund reference values (1.8 kN for women ≥60 years; 2.4 kN for women 50–60 years), the maximum spinal compression forces during manual pushing exceeded the 1.8 kN limit in 12 intervals and the 2.4 kN limit in 8. With assistance, these limits were exceeded in 9 and 2 intervals, respectively. Mean forces never exceeded 2.4 kN; the 1.8 kN limit was surpassed only twice without assistance and never with assistance.

The posture analysis shows that, across all intervals, the motorized wheel reduced both maximum and mean trunk inclination by an average of 18%, indicating a more upright posture compared to manual pushing, as illustrated in the Appendix (Fig. A.1).



	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
	*	*	*	*	*	*	*		*	*			*
☐ manual	2.4	2.7	2.9	2.5	2.1	2.2	4.1	2.0	2.9	3.4	1.8	3.0	2.7
☐ assist	2.0	2.2	2.2	1.6	1.9	1.8	2.8	1.8	2.3	2.2	1.7	2.7	2.2

	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
	*		*	*	*		*		*	*			*
☐ manual	1.6	1.4	1.4	1.0	1.3	1.1	2.3	1.0	1.6	2.1	1.1	1.2	1.2
☐ assist	1.3	1.3	1.2	0.9	1.2	1.1	1.7	1.0	1.4	1.5	1.1	1.1	1.1

Fig. 5. Comparison of maximum (top) and mean (bottom) spinal compression forces at L5/S1 across the respective intervals. Gray bars: manual movement; blue bars: motorized assistance. * denotes significant differences (p < .05). Red lines: Dortmund reference values; dashed line: threshold for women > 60 years (1.8 kN); solid line: threshold for women aged 50–60 years (2.4 kN).

3.4 Muscular Strain

Motorized assistance during hospital bed pushing reduced muscle activity across all investigated muscle groups (DA, TPD, ES), with greater reductions generally observed on the left than on the right side.

For the **DA,** left-side activity was highest during manual pushing in *Pushing start phase ramp +3.5%* (27.9 ± 10.9 %MVIC) and was significantly lower in 8 of 13 intervals ($p \leq .022$), with the largest reduction of 18.7 %MVIC (−67%, Interval 10). On the right side, significant decreases occurred in only one interval ($p = .01$, Interval 9), while two intervals showed significant increases ($p < .001$, Intervals 5 and 11).

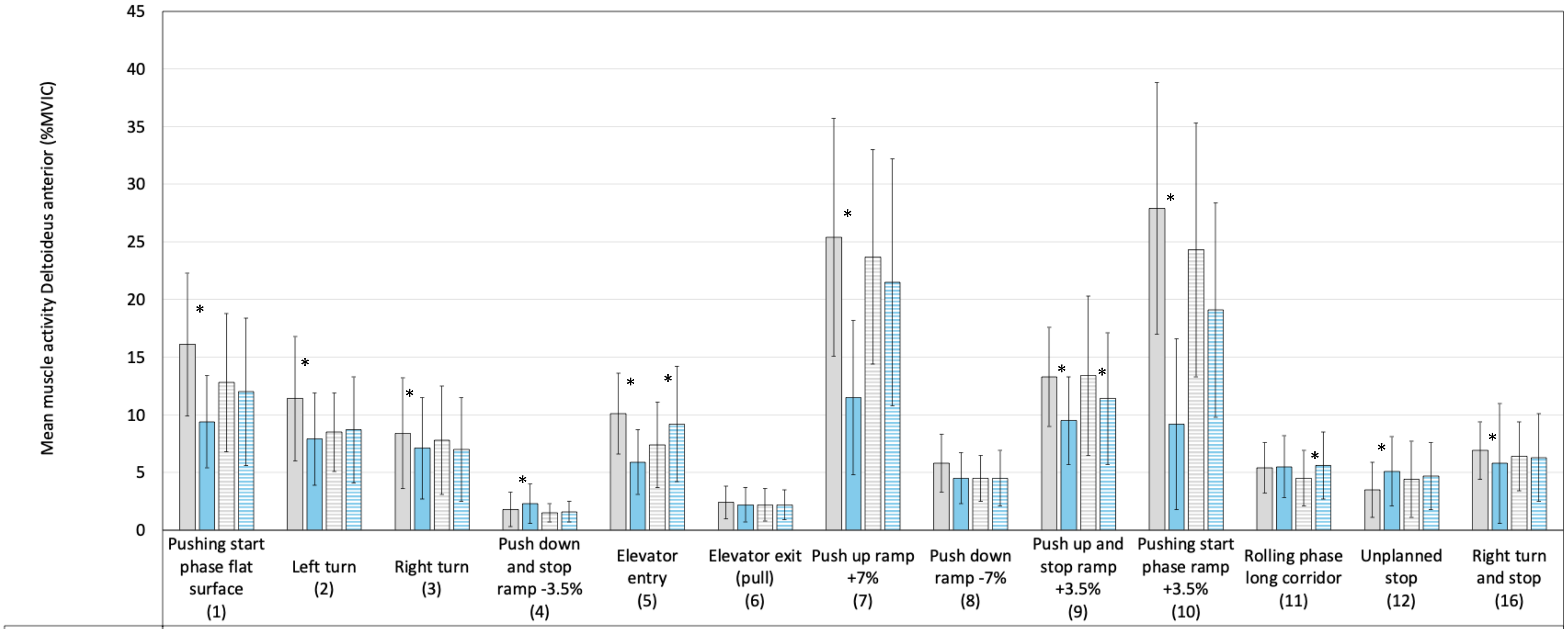
Over the entire course, left DA activity decreased by 4 %MVIC (−38%) and right DA by 0.6 %MVIC (−6%). A detailed interval breakdown is provided in Fig. 6.

For the **TPD**, significant reductions occurred in 5 of 13 intervals on the left ($p \leq .047$; Intervals 1, 5, 7, 9, 10) with a maximum of 9.6 %MVIC (−53%) in *Pushing start phase ramp +3.5%*. In *Push down and stop ramp −3.5%*, left TPD activity increased slightly (+0.4 %MVIC, $p = .02$). On the right, reductions occurred in 6 intervals ($p \leq .037$; Intervals 1, 4, 6, 7, 9, 10) with a maximum of 3.6 %MVIC (−26%, Interval 10).

Across the course, left TPD activity decreased by 1.7 %MVIC (−19%) and right TPD by 0.7 %MVIC (−8%). A detailed interval breakdown is provided in Appendix, Fig. A.2.

For the **ES**, left-side reductions were significant in 5 intervals ($p \leq .03$; Intervals 4, 7, 8, 9, 16), with the largest in *Push down and stop ramp −3.5%* (−3.1 %MVIC, −24%). On the right, reductions occurred in 7 intervals ($p \leq .02$; Intervals 1, 4, 5, 6, 7, 9, 10) with a maximum of 5.9 %MVIC (−33%) in *Pushing start phase ramp +3.5%*.

Over the course, left ES activity decreased by 1.7 %MVIC (−19%) and right ES by 1.3 %MVIC (−15%). A detailed interval breakdown is provided in Appendix, Fig. A.3.



	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(16)
■ manual left mus.	16.1	11.4	8.4	1.8	10.1	2.4	25.4	5.8	13.3	27.9	5.4	3.5	6.9
🟦 assist left mus.	9.4	7.9	7.1	2.3	5.9	2.2	11.5	4.5	9.5	9.2	5.5	5.1	5.8
▤ manual right mus.	12.8	8.5	7.8	1.5	7.4	2.2	23.7	4.5	13.4	24.3	4.5	4.4	6.4
▤ assist right mus.	12.0	8.7	7.0	1.6	9.2	2.2	21.5	4.5	11.4	19.1	5.6	4.7	6.3

Fig. 6. Comparison of mean muscle activity of the anterior shoulder muscles (Deltoideus anterior) measured across the respective intervals. Gray bars represent manual pushing; blue bars represent pushing with motorized assistance. Dashed bars refer to the right muscle, and fully filled bars refer to the left muscle of the participants. * de-notes significant differences (p < .05) in the analyzed intervals.

3.5 Perceived Strain and User Satisfaction

Fig. 7 shows the average ratings of perceived physical exertion for moving the hospital bed with and without motorized assistance.

The difference between both conditions was statistically significant (*p* < .001). Manual pushing was rated on average at 6.4 ± 2.0, corresponding to a perception of "strong to very strong" exertion. With motorized assistance, the rating dropped to 2.0 ± 0.9, indicating a low level of physical effort.

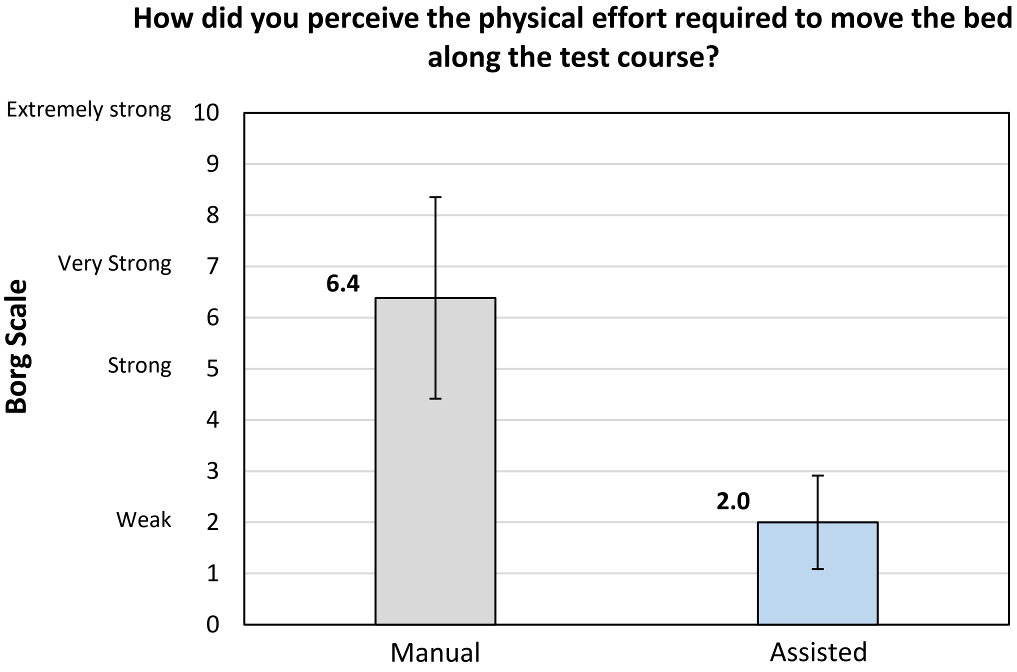


Fig. 7: Mean Borg scale rating and standard deviation across all participants for the test course under manual (gray) and assisted (blue) conditions.

User acceptance ratings (scale: 0–100) differed significantly between manual pushing and motorized assistance (p < .001). Manual pushing received an average score of **54 ± 22**, indicating adequate but improvable acceptance, whereas motorized assistance scored **86 ± 11,** corresponding to “excellent” acceptance.

4 Discussion

4.1 Exerted Forces

The results demonstrated that motorized wheel significantly reduced maximum hand forces in 10 of 13 intervals and mean hand forces in 12 intervals. The relief was particularly pronounced in the ramp intervals, with a reduction of up to 45%.

The measured exerted forces were within the ranges reported in previous studies. Brütting et al. (2017) reported mean forces between 54 ± 19 N and 79 ± 7 N and peak values up to 334 N when untrained individuals moved a hospital bed. In this study, manual pushing produced similar mean forces (51 ± 12 N to 111 ± 18 N) but lower peaks (231 ± 48 N, Interval 1), likely because trained nursing staff accelerated more smoothly. Peak forces (222 ± 49 N) were consistent with Leban et al. (2022), though mean forces here were higher (111 ± 18 N vs. 68 ± 17 N), probably due to measuring the full 3D force vector rather than only the X-direction, and differences in interval duration affecting steady-rolling phases.

A comparison with the EN 60601-2-52:2016-04 standard shows that the threshold value of 160 N for accelerating a bed from a standstill was exceeded in all relevant intervals (1, 5, 6, 7, and 10), both with and without motorized assistance. Meeting this limit would require stronger motor support or slower acceleration by nursing staff. However, because the motorized wheel is mounted laterally at the foot end, increasing power would amplify a pulling tendency toward one side. In this study, left-side mounting caused a slight rightward drift during straight-line motion.

This effect was most evident in the EMG data. During the start phase on level ground, the left DA showed a substantially greater reduction in activity (6.7 %MVIC) than the right DA (0.8 %MVIC). During the rolling phase, right DA activity was even significantly higher with motorized assistance than with manual pushing, although the difference was small at 1.1 %MVIC. Several participants reported the rightward pull but did not perceive it as disruptive, as reflected in high user-acceptance ratings. Nevertheless, a further increase in motor power could amplify this pulling tendency and impair maneuverability.

A central “fifth wheel” design could avoid lateral pulling. Matz and Morgan (2018) reported that centrally mounted systems also reduced ramp forces by 43–60%. In this study, the maximum ramp reduction was 45%. However, as most hospital beds are not equipped with a fifth wheel, retrofitting would require substantial effort and investment, and in some cases may not be feasible.

4.2 Spinal Compression Force at L5/S1

This study demonstrated that manually moving hospital beds, especially on ramps, places considerable strain on the lumbar spine. The highest maximum and mean compression forces at L5/S1 occurred during the *Pushing start phase ramp +3.5%* and *Push up ramp +7%* intervals, reaching maximum values of 3.4 kN and 4.1 kN, and mean values were 2.1 kN and 2.3 kN, respectively. Motorized assistance reduced these forces by up to 36%.

Brütting et al. (2017) reported mean spinal compression forces ranging from 0.7 ± 0.1–0.9 ± 0.2 kN and peak values between 1.4 kN and 2.9 kN when moving a bed loaded with a 100 kg dummy. Their study examined the rolling, braking, and start phases. In this study, manual pushing on level ground produced slightly higher mean compression forces (1.1 ± 0.1–1.6 ± 0.2 kN), while peak values ranged between 1.8 kN and 2.4 kN, within a comparable range.

The spinal compression forces determined in this study were compared with the revised Dortmund threshold values for women aged >60 years (1.8 kN) and those aged 50–60 years (2.4 kN). These thresholds were selected because approximately one-third of nursing staff in Germany are over 50 years old, and approximately 10% are over 60 years—a proportion that continues to rise (Deutsche Krankenhausgesellschaft, 2025).

The results of this study indicate that the maximum spinal compression force exceeded the 1.8 kN threshold in all intervals without motorized wheel assistance. With motorized assistance, this threshold was met or undercut in four intervals. The higher threshold for nursing staff aged 50–60 years (2.4 kN) was exceeded with motorized assistance only during the steepest ramp interval (7% incline).

Based on these findings, motorized wheels are recommended as standard equipment for moving hospital beds to reduce spinal load on nursing staff.

4.3 Muscular Strain

This study revealed that the motorized wheel significantly reduces strain on the shoulder and neck muscles, particularly during start phases. Although significant reductions in back muscle activity were also observed, they were less pronounced. Moreover, the relief was more substantial on the left side of the body than on the right.

To date, no comparable EMG studies have specifically examined the effects of motorized wheels on hospital beds. However, Daniell et al. (2014) and Guo et al. (2017) investigated muscular strain associated with the use of bed movers compared to manual pushing of beds or patient trolleys. Both studies reported reductions in muscle activity of up to 40%. Owing to methodological differences, such as joystick-based control, variations in course layout, and the use of nonprofessional participants in the study by Daniell et al., the findings are only partially comparable to the present investigation. Nonetheless, identical muscle groups were deliberately measured to determine the results of this study within the context of existing research.

For the ***M.* DA**, Guo et al. reported an activity level of 7.0 %MVIC during manual pushing, which was reduced by 15% with the use of a bed mover. In this study, asymmetrical activation was observed (left: 2.4–10.1 %MVIC; right: 2.2–8.5 %MVIC). For the ***M.* TPD**, values reported in the literature ranged from 5.0% MVIC (Daniell et al., 2014) to 9.0% MVIC (Guo et al., 2017). This study yielded comparable results (left: 5.6–9.3 %MVIC; right: 5.5–8.9 %MVIC). For the ***M.* ES**, reference values were approximately 10 %MVIC (Guo et al., 2017), and 7.8% (left) and 9.8% (right) in the study by Daniell et al. This study reported slightly higher values (left: 9.0–12.8 %MVIC; right: 9.9–12.6 %MVIC). Relief effects were observed only at specific intervals, such as during the right turn with a subsequent stop (left side), and when entering and exiting the elevator (right side), with reductions of up to 15%.

Overall, the results confirm that muscular strain during manual pushing was similar in magnitude to that reported in previous studies. The relief effects achieved through the motorized wheel were evident but smaller than those observed with bed movers, primarily because the motorized wheel offers only partial, rather than full, propulsion support.

4.4 Perceived Strain and User Satisfaction

The motorized wheel significantly reduced perceived physical exertion, with Borg scale ratings decreasing from 6.4 ± 2.0 to 2.0 ± 0.9. Similar findings were also reported by Wiggermann (2017), who assessed perceived exertion across specific route segments (hallway, ramp, elevator, unplanned Stop). In that study, Borg ratings for manual pushing ranged from 3.6 to 6.9, whereas the use of a motorized fifth wheel resulted in scores between 1.3 and 1.8.

While prior studies on support systems such as bed movers or motorized wheels have focused mainly on physical relief, usability has received little attention. High usability is crucial, as systems that are difficult to operate are unlikely to be adopted in fast-paced clinical environments. Therefore, usability was assessed in this study using the SUS. A new hospital bed, previously unfamiliar to the nursing staff, was evaluated as a "new product." The bed with the motorized wheel achieved an SUS score of 86 ± 11, which corresponds to "excellent usability" according to Bangor (2009). In contrast, the same bed without motorized assistance scored only 54 ± 22. Subjective feedback was predominantly positive, particularly regarding the absence of additional control elements and operation identical to a conventional bed.

A comparison of the relief effects on maximum and mean exerted forces suggests that this intuitive operation may also has disadvantages and initially limit the reduction of peak forces. Across the entire test course, the motorized wheel reduced mean exerted forces by 22% but peak values by only 16%. One possible explanation lies in user behavior: many nursing staff members continued to accelerate the motorized bed by leaning into it with their body weight, as they were accustomed to. However, in theory, a brief initial impulse would be sufficient to activate the motorized assistance. Greater experience with the system and targeted staff training could further enhance the reduction of peak forces.

4.5 Limitations

This study has several limitations. Walking speed was not standardized to simulate realistic working conditions. Participants were nursing staff from the test facility, and only one bed model was examined, which may limit generalizability. The motorized wheel was not tested under different loading conditions; future studies should assess its effectiveness with unloaded beds and bariatric loads.

Throughout the test, participants were required to hold the force measurement handles continuously. This does not fully reflect real-life handling scenarios, as caregivers often change hand positions or guide the bed from one side, particularly when turning or maneuvering. Furthermore, participants wore various types of work shoes, potentially affecting friction between shoe soles and the floor.

Another possible influence was that participants knew whether they were pushing the bed manually or with assistance, which may have biased perceived exertion and usability ratings. In particular, the novelty effect may play an important role. This effect refers to the increased attention and enthusiasm that new technology can generate among users, thereby enhancing the perceived usability of the product (Karapanos et al., 2009; Koch et al., 2018).

Finally, this study analyzed only a short, standardized test course, representing a limited segment of typical hospital bed transport tasks. Future research should assess exerted forces, L5/S1 compression, and muscle activity over full work shifts to provide a more comprehensive picture of the cumulative workload.

5 Conclusion

During manual pushing, the threshold values for both exerted forces and spinal compression were exceeded in most sections of the test course. The use of the motorized wheel significantly reduced both types of physical loads, allowing threshold values to be undercut at several intervals. However, the level of assistance was insufficient to meet these limits in all situations. In particular, nursing staff aged >60 years should continue to push beds on steep ramps in pairs or use bed-mover systems.

Although bed movers can significantly reduce physical strain, the TOP principles of occupational safety (technical, organizational, and personal) favor implementing technical solutions directly into the work equipment. Thus, an integrated drive system within the bed offers a more sustainable solution than external aids.

The system examined in this study represents a promising approach. It is currently the only known solution that can be retrofitted to hospital beds from various manufacturers by replacing one of the existing wheels. This creates the potential to physically relieve lots of nursing staff worldwide. The high usability demonstrated in this study indicates that the system can be used immediately without additional training.

A long-term analysis is desirable for a more comprehensive evaluation of its effectiveness. A longitudinal study could provide insight into how continuous use of motorized assistance systems affects muscle fatigue, secondary health effects, and the risk of MSDs over time.

Conflicts of interest: The authors declare that they have no conflict of interest.

Declaration of generative AI in scientific writing: The authors confirm that no content was generated using AI tools during the writing of this manuscript.

Author contributions: Niels Hinricher: Conceptualization, Methodology, Investigation, Writing – Original Draft, Funding acquisition, **Alina Bola:** Methodology, Investigation, Visualization, Writing – Original Draft, **Chris**

Schröer: Methodology, Investigation, Writing – Review & Editing, **Hendrik Ludewig:** Investigation, Visualization **Claus Backhaus:** Supervision

Funding: This study was funded by TENTE-ROLLEN GmbH (Wermelskirchen, Germany) and LINAK A/S (Nordborg, Denmark). The funders had no role in the study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Data statement: The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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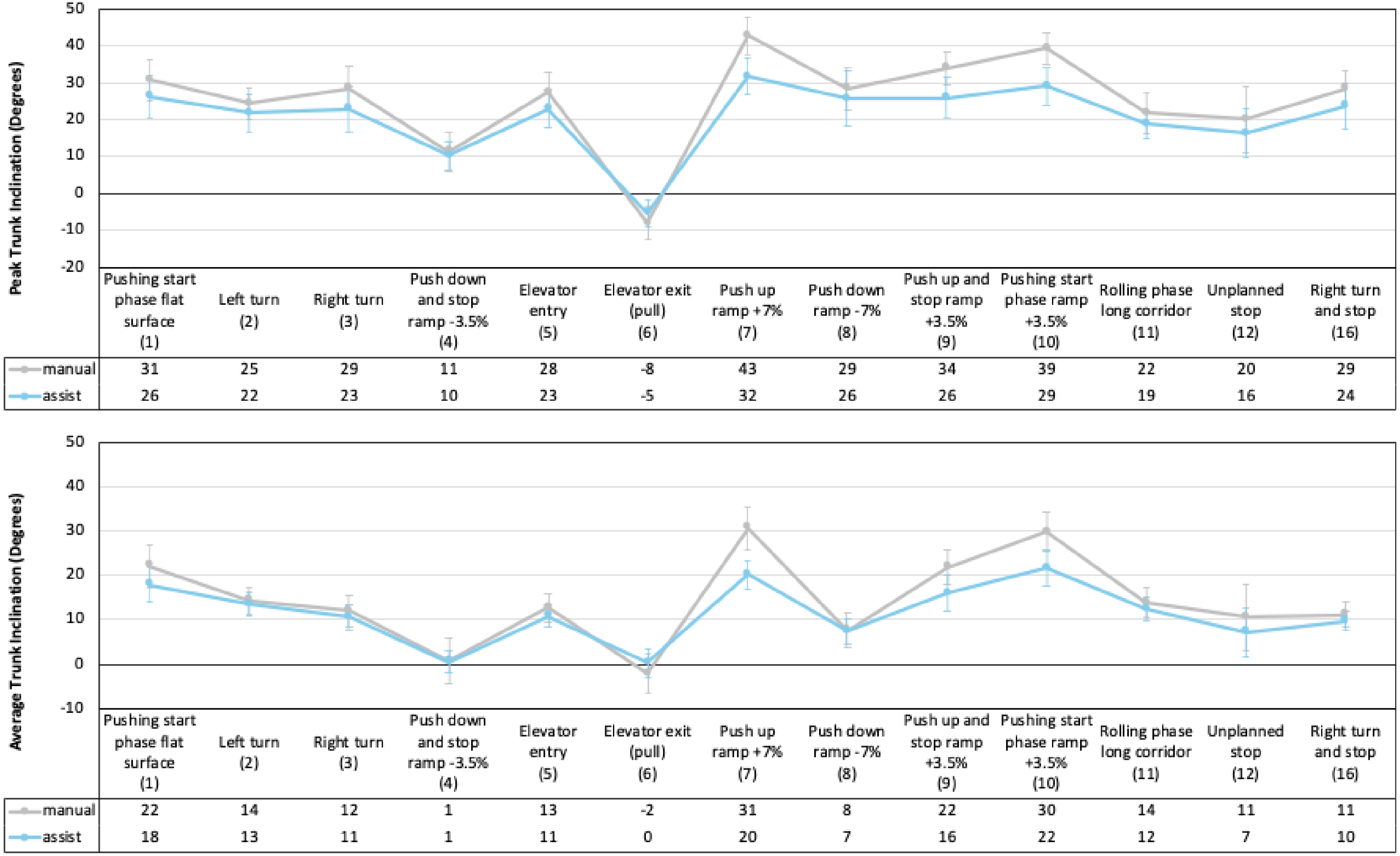
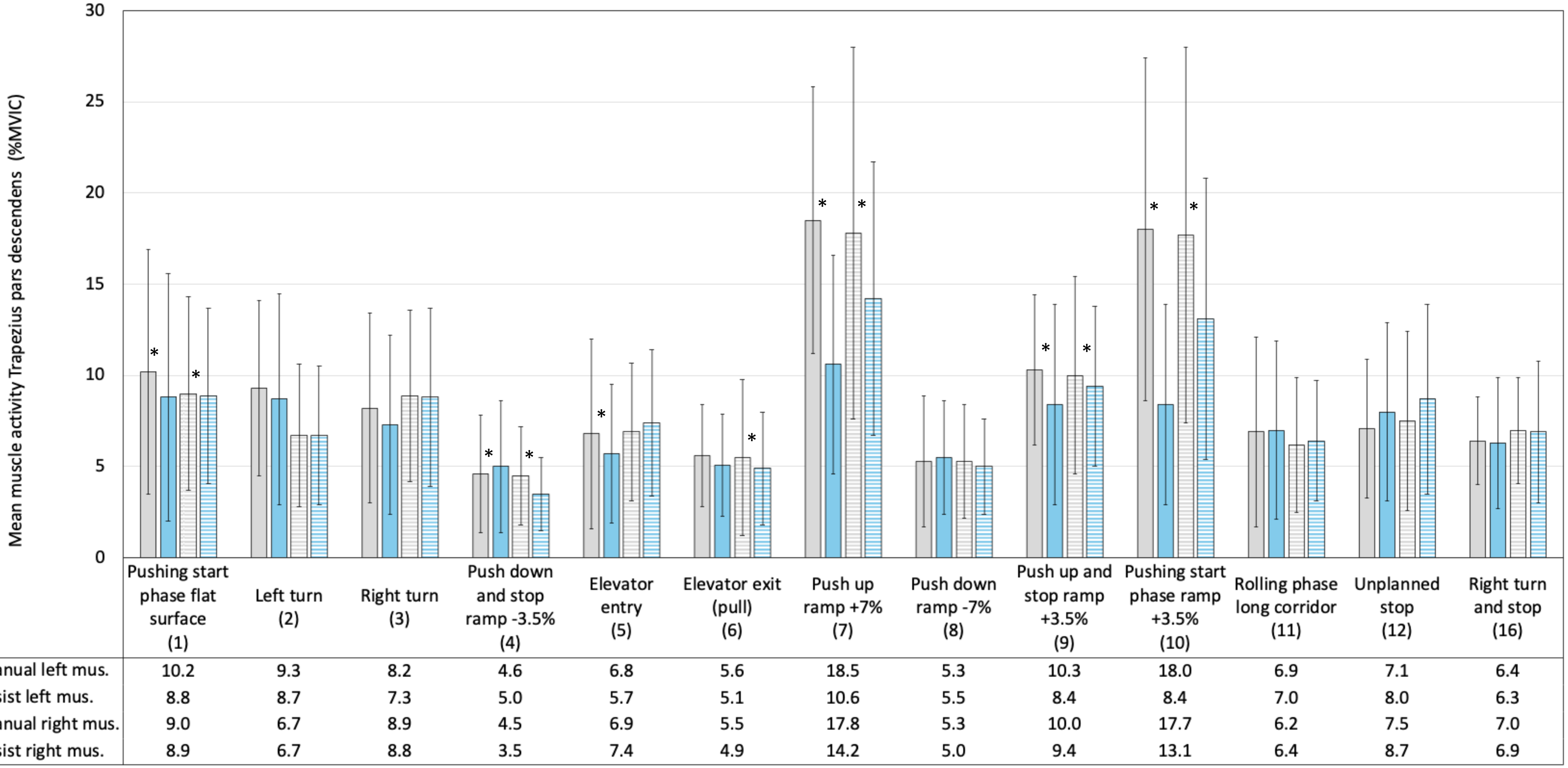
Appendix



	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
manual	31	25	29	11	28	-8	43	29	34	39	22	20	29
assist	26	22	23	10	23	-5	32	26	26	29	19	16	24

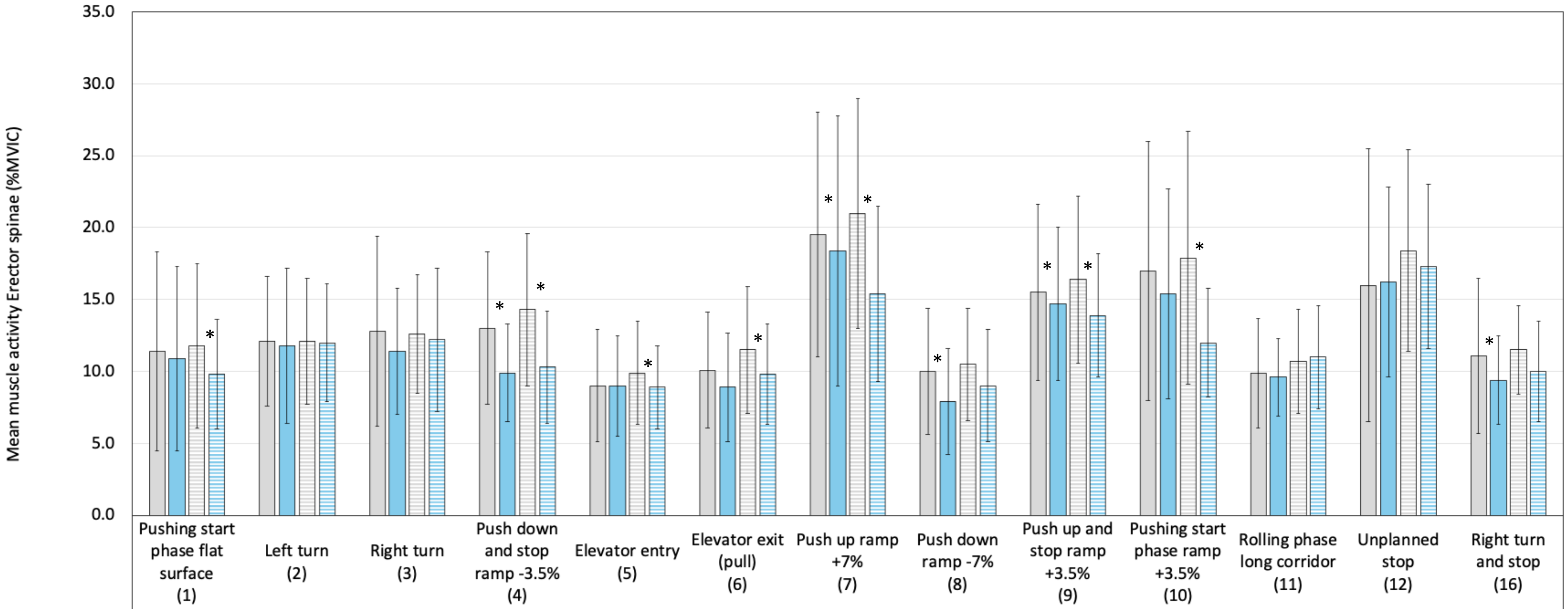
	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
manual	22	14	12	1	13	-2	31	8	22	30	14	11	11
assist	18	13	11	1	11	0	20	7	16	22	12	7	10

Fig. A.1. Comparison of averaged maximum trunk inclinations (top) and mean values (bottom) measured across the respective intervals. Gray lines represent manual pushing, and blue lines represent bed movement with motorized assistance.



	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
☐ manual left mus.	10.2	9.3	8.2	4.6	6.8	5.6	18.5	5.3	10.3	18.0	6.9	7.1	6.4
■ assist left mus.	8.8	8.7	7.3	5.0	5.7	5.1	10.6	5.5	8.4	8.4	7.0	8.0	6.3
▤ manual right mus.	9.0	6.7	8.9	4.5	6.9	5.5	17.8	5.3	10.0	17.7	6.2	7.5	7.0
▤ assist right mus.	8.9	6.7	8.8	3.5	7.4	4.9	14.2	5.0	9.4	13.1	6.4	8.7	6.9

Fig. A.2. Comparison of the mean muscle activity of the anterior neck muscles (TPD) measured within the respective intervals. The grey bars represent manual movement, while the blue bars indicate bed movement supported by the motorized wheel. Dashed bars refer to the right muscle, and solid bars to the left muscle of the participants. Significant differences (p < .05) within the examined intervals are marked with *.



	Pushing start phase flat surface (1)	Left turn (2)	Right turn (3)	Push down and stop ramp -3.5% (4)	Elevator entry (5)	Elevator exit (pull) (6)	Push up ramp +7% (7)	Push down ramp -7% (8)	Push up and stop ramp +3.5% (9)	Pushing start phase ramp +3.5% (10)	Rolling phase long corridor (11)	Unplanned stop (12)	Right turn and stop (16)
☐ manual left mus.	11.4	12.1	12.8	13.0	9.0	10.1	19.5	10.0	15.5	17.0	9.9	16.0	11.1
■ assist left mus.	10.9	11.8	11.4	9.9	9.0	8.9	18.4	7.9	14.7	15.4	9.6	16.2	9.4
▤ manual right mus.	11.8	12.1	12.6	14.3	9.9	11.5	21.0	10.5	16.4	17.9	10.7	18.4	11.5
▤ assist right mus.	9.8	12.0	12.2	10.3	8.9	9.8	15.4	9.0	13.9	12.0	11.0	17.3	10.0

Fig. A.3. Comparison of the mean muscle activity of the lower back muscles (erector spinae) measured within the respective intervals. The grey bars represent manual movement, while the blue bars indicate bed movement supported by the motorized caster. Dashed bars refer to the right muscle, and solid bars to the left muscle of the participants. Significant differences ($p < .05$) within the examined intervals are marked with *.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: