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Design and Ergonomic Evaluation of an Automated Wheelchair Lifting Aid for Caregiver Injury Prevention

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Abstract

Background: Manual handling during wheelchair loading and unloading imposes substantial biomechanical demands on caregivers, potentially contributing to work-related musculoskeletal disorders (WMSDs) because of non-neutral working postures and increased spinal loading, particularly at the L5/S1 lumbosacral junction.
Objective: This study proposes the design, development, and ergonomic evaluation of an electromechanical assistive lifting device integrated into the cargo compartment of a Toyota Avanza multipurpose vehicle (MPV).
Methods: A 12-V DC electric winch equipped with a swiveling boom arm and a quick-release sling harness was evaluated during caregiver-assisted wheelchair loading and unloading tasks involving three wheelchair configurations: a standard manual wheelchair (17 kg), a Type A powered wheelchair, and a Type B powered wheelchair (weighing up to 28 kg). Functional compatibility and observable caregiver working postures were assessed before and after device implementation.
Results: Automated lifting system successfully demonstrated proof-of-concept operation with all three wheelchair configurations. Compared with manual handling, assisted loading reduced the need for non-neutral caregiver postures, including approximately 30° of backward trunk extension and approximately 75° of asymmetric lower-extremity bracing. By replacing manual lifting effort with electromechanical assistance, the device enabled the caregiver to maintain a more upright working posture during the demonstrated operations. However, repeated trial counts were not documented; therefore, no statistical success rate or quantified reduction in biomechanical loading can be established.
Conclusion: Proof-of-concept device demonstrated functional feasibility and the potential to reduce non-neutral caregiver postures during wheelchair loading and unloading. Its integration into the vehicle cargo compartment offers a practical retrofit concept for assisted wheelchair transportation.

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INTRODUCTION

People with lower-limb disabilities may experience paralysis, muscle weakness, or restricted lower-extremity mobility that limits their ability to stand or walk independently (Widinarsih, 2019). Wheelchairs therefore support mobility and activities of daily living, while contemporary designs increasingly incorporate ergonomic and assistive features to improve postural support and mobility (Batan, 2007; Sinyukov et al., 2025; Yudiantyo, 2020; Yudiantyo et al., 2021). The transportation challenge addressed in this study arises when a wheelchair must be transferred into a passenger vehicle, a task that can impose substantial physical demands on the caregiver or other individual responsible for loading the wheelchair.

Although wheelchairs facilitate short-distance mobility in indoor environments, long-

distance travel often requires passenger vehicles to transport individuals with lower-limb disabilities and their mobility devices. However, the physical limitations experienced by drivers with disabilities may prevent them from independently lifting and loading their wheelchairs into vehicle compartments, thereby restricting their independent mobility (Klein, 1985). Furthermore, independent mobility cannot be achieved simply by remaining seated in a wheelchair inside a vehicle, as standard wheelchairs are not designed or tested to function as motor vehicle seats. Their structural performance under frontal-impact conditions may be inadequate, as demonstrated by sled-test investigations (Bertocci et al., 2001).

Using a wheelchair as a vehicle seat therefore raises significant safety concerns during transit and exposes manufacturers to substantial product liability risks (Joint Committee on Mobility for Disabled People, 1997). Consequently, safe transportation generally requires wheelchair users to transfer to standard vehicle seats, with their wheelchairs separately secured in designated storage areas (Joint Committee on Mobility for Disabled People, 1997). Accordingly, the target operator evaluated in this study is the caregiver or helper responsible for loading and unloading the wheelchair after the wheelchair user has transferred to a standard vehicle seat. Independent operation by wheelchair users is outside the scope of this evaluation.

Once an individual with a lower-limb disability has transferred into a vehicle, the wheelchair must subsequently be lifted and loaded into the vehicle compartment. Although previous ergonomic innovations have focused on facilitating wheelchair propulsion through improved handle designs Yudiantyo (2020), the physical exertion associated with transferring and loading mobility devices remains substantial and is strongly associated with chronic back pain. Changing transportation modes, particularly transferring from a wheelchair to a passenger vehicle and loading the wheelchair into the vehicle, represents one of the primary barriers to independent mobility (Madej et al., 2023).

Biomechanical investigations have identified wheelchair loading into passenger vehicles as a task frequently associated with substantial physical strain and lumbar discomfort (Haubert et al., 2015). Although powered electric lifts can effectively reduce the physical loads imposed on caregivers' arms, shoulders, and backs during single-person transfer tasks Tang et al. (2018), commercially available lifting devices may be excessively heavy, expensive, and difficult to install or operate across different vehicle types (Tang et al., 2018). Consequently, interactions among individuals with disabilities, caregivers, wheelchairs, and motor vehicles continue to present substantial operational challenges Sydor et al. (2023), underscoring the need for accessible and ergonomically designed wheelchair loading assistance devices (Tang et al., 2018).

To accommodate individuals who require wheelchair-based transportation, motor vehicles equipped with specialized lifting systems, which can be expensive, are often necessary (Madej et al., 2023). Furthermore, beyond the loading process, wheelchair users must ensure that their wheelchairs are securely restrained within the vehicle during transit to prevent hazards associated with sudden maneuvers or collisions (Miyawaki et al., 2012). To address operational accessibility and transportation safety, this study aims to design and ergonomically evaluate an electric wheelchair lifting aid for caregiver-assisted loading and unloading in a passenger vehicle. The evaluation focuses on functional compatibility with three wheelchair configurations, observable changes in caregiver posture during loading and unloading, and the stability of the wheelchair's in-vehicle securing mechanism. Based on ergonomic principles, tasks should be performed with minimal physical effort while ensuring ease of operation, comfort, and safety (Iridiastadi. & Yassierli, 2014). The proposed design also incorporates a dedicated in-vehicle securing mechanism to keep the stored wheelchair stable and restrained during travel, particularly when navigating uneven or winding roads (Hryciów, 2022). Accordingly, this study evaluates a proof-of-concept retrofit system rather than independent wheelchair-user operation or population-level injury prevention.

METHOD

This research adopted a structured product development methodology that integrated human-centered ergonomic principles into the design of an electric wheelchair lifting aid. As illustrated in Figure 1, the study synthesized theoretical ergonomic principles, product design methodologies, and sequential engineering procedures to develop an appropriate technical

solution. The framework comprised four interconnected layers. The first layer, the research foundation, established the central objective of mitigating physical strain and back pain associated with manual wheelchair loading and unloading, guided by structured product development principles (Pahl et al., 2007). The second layer, the integrated ergonomic core, incorporated human factors into design decisions to ensure ease of use, operational safety, and physical comfort (Pahl et al., 2007). The third layer, the engineering design process, implemented a systematic sequence of activities adapted from established product development stages (Ulrich, 2008). The fourth layer, the target deliverable, encompassed the mechanical lifting aid and its integrated in-vehicle securing mechanism (Miyawaki et al., 2012).

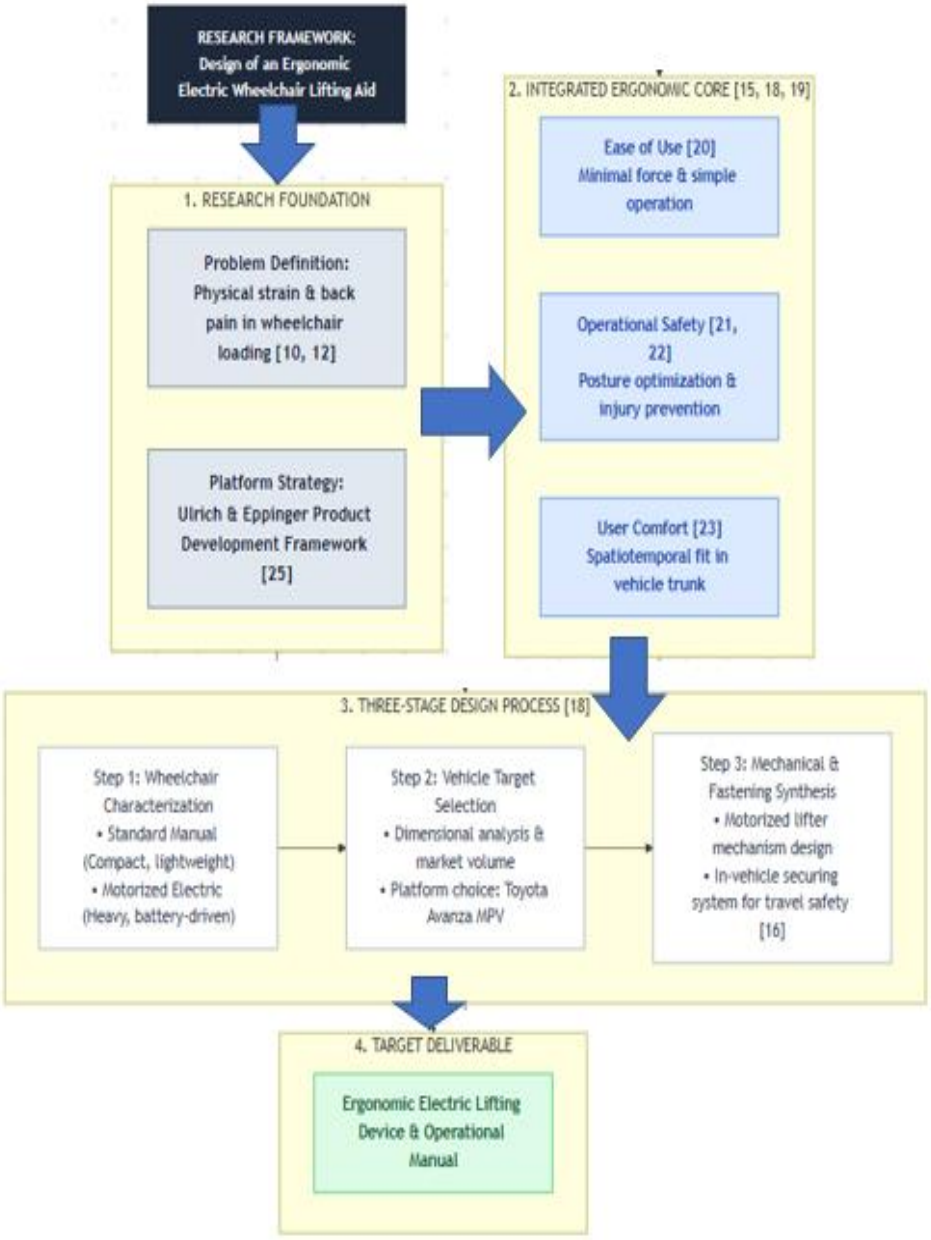


Figure 1. Research Framework

Ergonomics is defined as a multidisciplinary field that examines human capabilities, limitations, and characteristics to optimize the design of products, systems, and environments, thereby promoting health, safety, and operational efficiency (Nurmianto, 1996). In this study, ergonomic principles were applied to three core operational objectives for the wheelchair lifting aid: ease of use, achieved by minimizing the physical force and effort required during loading and unloading, thereby reducing the physical demands on the operator; safety, addressed by minimizing the risk of acute injuries and long-term musculoskeletal disorders (MSDs) through the

avoidance of awkward or extreme biomechanical postures; and comfort, addressed by ensuring physical accessibility and adequate functional clearance within spatially constrained environments, particularly vehicle trunks.

From a product engineering perspective, product design aligns user needs with functional and technological requirements to develop viable technical solutions (Ulrich, 2008). Although commercialization was beyond the scope of this study, the development process followed the platform product development framework established by Ulrich (2008), adapted through systematic engineering design stages. The overall procedure comprised four sequential phases: idea identification, problem definition, detailed product design, and prototyping and design finalization (Ulrich, 2008). The foundational ideas and problem statements were presented in the Introduction, whereas the prototyping process and final evaluation are presented in the Results and Discussion section.

The detailed engineering design process was carried out through three structured stages. The first stage involved evaluating the physical specifications, structural weights, and folding mechanisms of two distinct wheelchair types: standard manual wheelchairs, representing relatively lightweight and compact models, and motorized electric wheelchairs, which generally have greater mass and spatial dimensions because of their integrated battery systems and drive motors. The second stage involved determining the target vehicle platform based on dimensional clearance, trunk geometry, and market prevalence, with a particular focus on multipurpose passenger vehicles. The Toyota Avanza was selected as the reference vehicle platform because of its substantial market presence, widespread availability, suitable trunk dimensions, and structural compatibility with the proposed assistive device. The third and final stage involved integrating wheelchair dimensional parameters with vehicle spatial constraints to develop the electric lifting mechanism. During this stage, material selection, motor drive specifications, and structural load paths were determined to facilitate automated wheelchair loading and unloading. An in-vehicle securing mechanism was also incorporated to maintain wheelchair stability during transportation (Miyawaki et al., 2012). Finally, the operational procedures were documented to support the practical implementation of the proposed system.

RESULTS AND DISCUSSION

Results

Types of Wheelchairs

Mobility-assistance technology primarily classifies wheelchairs into two main operational categories: standard manual wheelchairs and motorized electric wheelchairs. Standard manual wheelchairs rely on human power, either through self-propulsion by the user or propulsion by a caregiver. They typically feature lightweight frames and cross-brace mechanisms designed to facilitate manual folding. Conversely, motorized electric wheelchairs incorporate battery packs, electric drive motors, and electronic control units (e.g., joysticks). Although electric wheelchairs provide greater autonomy for users with severe upper-extremity limitations, their integrated mechanical and electrical components substantially increase their overall mass, structural rigidity, and spatial requirements during vehicle-loading operations. To ensure that the proposed electric lifting aid accommodates different wheelchair configurations, both categories were analyzed based on their physical dimensions, folding configurations, and spatial requirements within the vehicle's cargo compartment.

Standard Manual Wheelchairs

Standard manual wheelchairs are among the most widely used mobility devices because of their structural simplicity, affordability, and compact footprint. The structural dimensions of the standard manual wheelchair evaluated in this study are presented in Table 1. Figure 2 illustrates the wheelchair in its fully unfolded operational configuration, whereas Figure 3 depicts its folded configuration for storage.

Table 1
Dimensions of a Standard Wheelchair

Specification	Folded	Opened
Length (cm)	105	105
Width (cm)	26	66
Height (cm)	87	87
Distance between front wheels (cm)	17	–
Distance between rear wheels (cm)	21	60
Front wheel width (cm)	2.5	2.5
Rear wheel width (cm)	2.5	2.5
Weight (kg)	17	17



Figure 2. Standard wheelchair in the open position



Figure 3. Standard wheelchair in folded condition

Motorized Electric Wheelchairs

Unlike manual wheelchairs, motorized electric wheelchairs utilize electric propulsion systems and relatively heavy battery packs. These components significantly enhance user independence but introduce additional physical and spatial challenges during vehicle-loading operations. To account for structural variations among commercially available models, two distinct electric wheelchair configurations, designated Type A and Type B, were evaluated based on their frame geometries and folding mechanisms.

Type A represents an integrated electric wheelchair featuring a front-folding mechanism with vertical movement. Its frame design allows the wheelchair to be folded by lifting and pivoting the seat structure from the front, resulting in a distinct storage configuration. Because several dimensions reported in Table 2 are greater in the folded configuration, these measurements should be interpreted as orientation-specific dimensional data rather than as evidence that all linear dimensions decrease during folding. The complete physical dimensions and overall mass of

Electric Wheelchair Type A are presented in Table 2. Its unfolded operational configuration and folded storage configuration are illustrated in Figures 4 and 5, respectively.

Table 2
Dimensions and Weight of Electric Wheelchair Type A

Specification	Unfolded	Folded
Length (cm)	35	90
Width (cm)	60	55
Height (cm)	80	90
Distance between front wheels (cm)	52	102
Distance between rear wheels (cm)	59	52
Front wheel diameter (cm)	4.5	4.5
Rear wheel diameter (cm)	5.5	5.5
Weight (kg)	28	28



Figure 4. Unfolded Type A



Figure 5. Folded Type A

Similar to Type A, Electric Wheelchair Type B features a folding mechanism; however, it employs a distinct lateral folding configuration that changes its storage profile within the vehicle's cargo compartment. Additionally, Type B features a modular power system in which the battery pack can be detached and transported separately. This modular configuration reduces the mass of the main wheelchair chassis by 8.515 kg during manual or assisted handling when the battery is removed. The complete dimensional specifications are summarized in Table 3, while Figures 6 and 7 illustrate the wheelchair in its unfolded and folded configurations, respectively.

Table 3
Dimensions and Weight of Motorized Electric Wheelchair Type B

Specification	Unfolded	Folded
Length (cm)	90	113
Width (cm)	45	70
Height (cm)	80	94
Distance between front wheels (cm)	26	50
Distance between rear wheels (cm)	34	56
Front wheel diameter (cm)	5	5
Rear wheel diameter (cm)	4	4
Weight (kg)	27	27
Wheelchair + Battery weight (kg)	35.5	35.5



Figure 6. Unfolded Type B

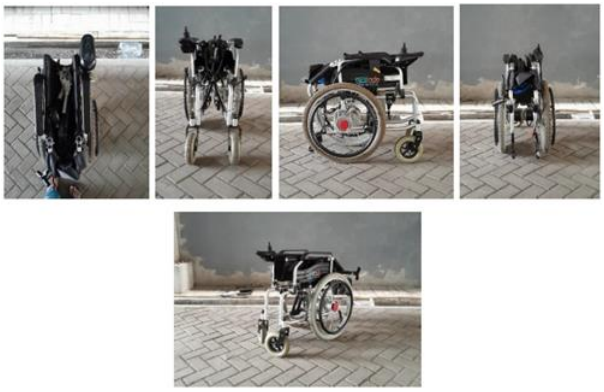


Figure 7. Folded Type B

Design Vehicle Platform

Selecting an appropriate target vehicle platform is a critical step in the platform product development strategy Ulrich (2008), ensuring that the designed assistive device can accommodate realistic automotive spatial constraints. The vehicle selected as the reference platform for this design is the Toyota Avanza, a widely used multipurpose vehicle (MPV) in the Indonesian automotive market. The engineering design specifically focuses on the rear cargo compartment (trunk), which serves as the primary operational space for wheelchair loading, unloading, and securing. Figure 8 illustrates the geometry and spatial configuration of the selected vehicle's cargo compartment, while the interior dimensions and available clearances, corresponding to the reference points labeled in Figure 9, are summarized in Table 4.

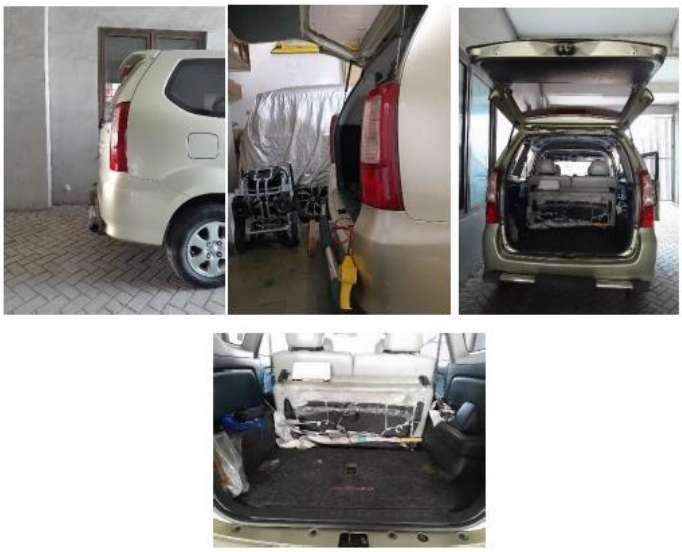


Figure 8. Toyota Avanza cargo area (trunk)



Figure 9. Trunk dimension reference points

Table 4
Trunk Dimensions

Reference Point	Dimension	Value (cm)
A	Width of the trunk from left to right	109
B	Height of the trunk from the ground	56
C	Height of the trunk from the top	100
D	Depth of the trunk from the edge of the door to the back (including the backrest)	76

Biomechanical and Postural Analysis of the Helper

Manual handling during wheelchair loading and unloading exposes caregivers to considerable biomechanical stress. A helper with an approximate stature of 160 cm may experience substantial physical strain when transferring a wheelchair from the ground into the vehicle's trunk (Sydor et al., 2023). As illustrated in Figure 10(a), after initially lifting the wheelchair from ground level, the helper must stabilize and balance its mass against the left thigh and abdominal region because of spatial constraints and the wheelchair's overall dimensions (Sydor et al., 2023). In this awkward intermediate posture, the helper gradually moves forward to position the wheelchair frame on the outer threshold of the vehicle's cargo platform.

Once the wheelchair rests on the platform edge, the helper adjusts to an upright standing

posture and manually pushes the device into the cargo compartment using both hands (Yudiantyo, 2020). Conversely, the unloading procedure involves the reverse sequence of movements: the wheelchair is pulled toward the platform edge, dynamically stabilized against the thigh and abdomen to control its downward movement, and subsequently lowered to the ground. The source documentation identifies the photographed helper only by an approximate stature of 160 cm and does not provide a complete demographic profile, health history, or repeated-participant assessment. Accordingly, the postural comparison is treated as a proof-of-concept task observation rather than a population-level ergonomic study. Formal documentation of ethics approval or exemption is not reported in the available manuscript record, which constitutes a limitation of the present study.



Figure 10. Helper's extreme posture (a) and posture angle (b)

Biomechanical evaluation of the postures during these task cycles (Figure 10b) reveals substantial angular deviations from neutral joint alignment. Specifically, the helper exhibits approximately 30° of backward trunk extension relative to the vertical axis, accompanied by approximately 75° of right-leg abduction relative to the normal anatomical standing posture. This combination of substantial trunk extension and asymmetric lower-extremity stabilization is consistent with postures associated with increased lumbar loading. According to ergonomic and human factors principles, performing manual lifting tasks in extreme non-neutral postures can substantially increase biomechanical demands and exceed recommended exposure limits (Stanton, 2018).

Repeated exposure to these biomechanical demands without specialized lifting assistance Tang et al. (2018) increases the risk of work-related musculoskeletal disorders (WMSDs), particularly lower-back pain and upper-extremity musculoskeletal injuries among caregivers. The approximately 30° trunk-extension and 75° leg-abduction values were estimated through observational assessment of static task photographs rather than instrumented motion capture, goniometry, or force measurement. Therefore, these angles should be interpreted as approximate postural observations.

To mitigate the biomechanical risks associated with the non-neutral postures described above, an automated assistive lifting device was engineered to reduce the need for manual lifting and lowering. Because the primary postural deviations and potential spinal overloading occur during the vertical elevation and descent of the wheelchair, the proposed intervention specifically automates these vertical transfer phases (Stanton, 2018). Based on ergonomic risk-prevention principles, the system developed in this study employs an electrically driven lifting and lowering mechanism, thereby replacing much of the manual physical exertion with electromechanical power to improve caregiver safety and operational efficiency (Tang et al., 2018).

Engineering Design of the Electric Lifter

To avoid extreme manual handling postures and minimize physical exertion, an electromechanical auxiliary lifting system was designed and integrated into the vehicle's trunk, as illustrated in Figure 11. The proposed electric lifter comprises three primary structural components: a mounting base (E), a vertical structural column (F), and a rotatable boom arm (G), together with an electric winch assembly (H). The structural base (E) is fabricated from a 7-mm-thick structural steel plate. This thickness was selected to provide sufficient structural rigidity and a stable mounting foundation, ensuring that the lifting assembly remains securely anchored to the

trunk floor during load transfers. The vertical column (F) consists of a hollow circular steel section with an outer diameter of 6 cm. Its height is constrained by the available vertical clearance within the vehicle's trunk (100 cm), resulting in a selected column height of 90 cm to maximize vertical lifting clearance while preventing interference with the upper trunk structure.

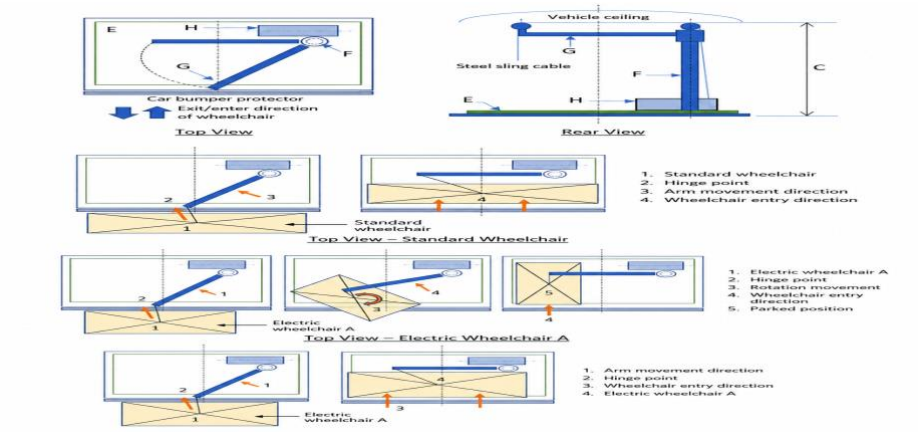


Figure 11. Design of the electric lifter for the car trunk (not to scale)

The length of the boom arm (G) was determined through spatial-clearance calculations based on the longitudinal dimension of a standard manual wheelchair (105 cm). A length of 55 cm, representing slightly more than half the wheelchair's overall length, was selected to position the lifting point approximately above the wheelchair's center of mass during loading. The boom arm is equipped with two guide pulleys to support and direct the high-tensile steel wire rope. Furthermore, the arm features a 360° rotary joint around the vertical column axis, enabling manual rotation to accommodate different wheelchair positions during lifting, swinging, and placement operations.

The lifting actuator (H) consists of a 12-V DC electric vehicle winch powered by the vehicle's electrical system. With a rated maximum lifting capacity of 100 kg, the winch provides a substantial nominal capacity margin for handling standard wheelchairs and motorized electric models weighing up to 28 kg. To maintain structural integrity, alignment, and resistance to vibration during vehicle operation, the structural assembly is joined using electric arc welding. The bill of materials and mechanical specifications of the lifting assembly are summarized in Table 5.

Table 5
Specifications of the Electric Lifter

Component	Material	Dimensions (cm)	Considerations
E. Base	Steel plate	100 (l) × 64 (w) × 5 (t)	Rigid enough to support the winch
F. Pole	Round hollow steel	Diameter 6, height 90	Max. height 100 cm of floor to roof (C); max. wheelchair seat height 80 cm
G. Arm	Steel frame	Length 55, height 5	Half the max. length of the wheelchair
H. Lifter	Vehicle electric winch; load capacity 100 kg; DC 12 V; steel sling rope	29 (l) × 12 (w) × 11 (t)	Car accessory; sized to max. wheelchair weight and vehicle power supply; sling strong enough for lifting

Functional Testing of the Electric Lifter

To evaluate the operational performance and structural functionality of the engineered electromechanical lifting system, loading and unloading trials were conducted using the installed

prototype inside a Toyota Avanza MPV. The experimental procedure assessed the operation of the system with three distinct wheelchair configurations: a standard manual wheelchair, a Type A motorized electric wheelchair, and a Type B motorized electric wheelchair. The objective was to determine whether the 12-V DC winch mechanism, rotatable boom arm, and custom lifting-sling attachment could accommodate different frame geometries, folding configurations, and wheelchair masses without operational interference (Ulrich, 2008).

The initial functional evaluation involved the standard manual wheelchair (mass: 17 kg). The lifting and loading procedure consisted of four sequential operational steps, illustrated in Figure 12. First, the high-tensile steel wire rope and lifting sling were securely attached to the structural frame of the folded manual wheelchair using the quick-release sling attachment. Second, the operator pressed the upward-direction control button on the remote-control unit, activating the 12-V DC electric winch to raise the wheelchair vertically from the ground until its base cleared the lower edge of the vehicle's trunk opening. Third, the operator manually rotated the boom arm around the vertical column axis, guiding the suspended wheelchair through the trunk opening and into the cargo compartment. Fourth, once the wheelchair was aligned within the cargo compartment, the operator pressed the downward-direction control button to lower it until its base rested securely on the support platform. The lifting sling was maintained under tension to provide an additional restraint point and help prevent movement during vehicle operation (Miyawaki et al., 2012).

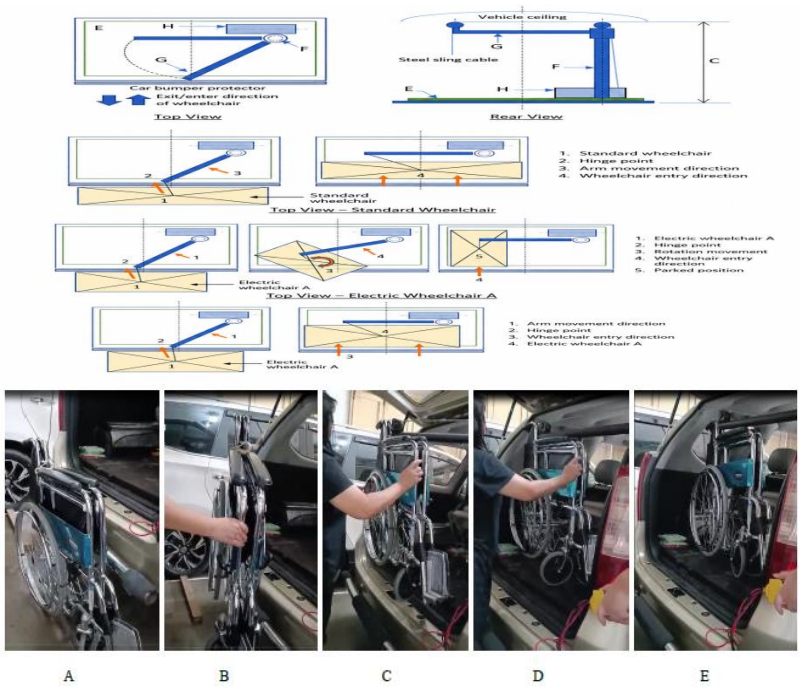


Figure 12. Steps for inserting a standard wheelchair (a) and the corresponding loading sequence (b)

The functional loading procedure was subsequently extended to the Type A motorized electric wheelchair (total mass: approximately 28 kg). Because of its greater mass and integrated battery assembly, particular attention was given to positioning the lifting sling to align the suspension point as closely as possible with the wheelchair's center of gravity. The loading and securing procedure, illustrated in Figure 13, consisted of five steps. First, the wheelchair was attached to the lifting assembly using the supplied lifting sling, with the attachment positioned to maintain balance during suspension. Second, the wheelchair was raised from the ground by pressing and holding the upward-direction button on the remote-control unit until the chassis completely cleared the lower edge of the vehicle's trunk opening. Third, the suspended wheelchair was manually rotated approximately 90° around its vertical suspension axis to orient its profile for the available trunk clearance. Fourth, the operator rotated the boom arm to guide the wheelchair into the trunk compartment. Fifth, once the wheelchair reached its designated storage

position, the operator pressed the downward-direction button to lower it until its base rested securely on the support platform. The upper frame remained supported by the tensioned lifting sling while the base rested on the platform, creating a two-point support arrangement intended to limit displacement during vehicle movement.

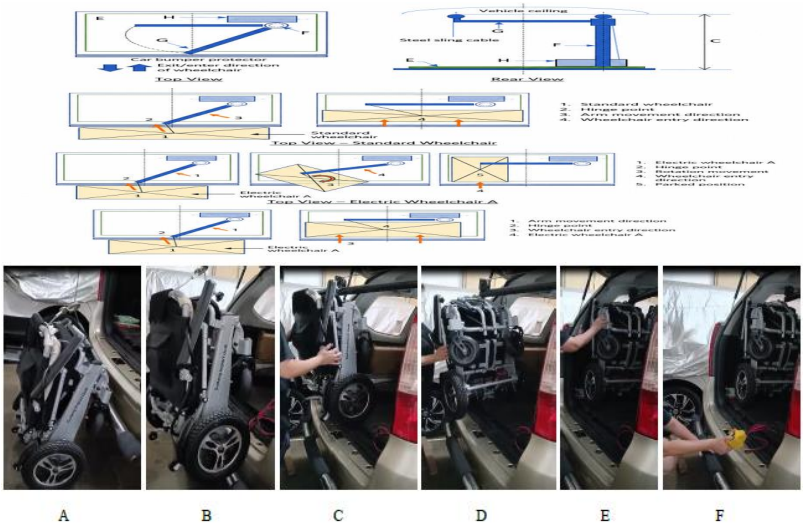


Figure 13. Steps for inserting an electric wheelchair Type A (a) and the corresponding loading sequence (b)

The final functional evaluation involved the Type B motorized electric wheelchair, which features a lateral folding mechanism and a detachable battery pack. The battery mass was reported as 8.515 kg. Its modular design allows the operator to detach the battery before lifting, thereby reducing the mass of the chassis during transfer operations. The loading and securing procedure for the Type B model, illustrated in Figure 14, followed a structured sequence. First, the wheelchair frame was securely attached using the high-tensile steel lifting sling, with the attachment points adjusted to accommodate its laterally folded configuration. Second, the wheelchair was raised from the ground by pressing and holding the upward-direction control button until the chassis cleared the lower edge of the vehicle's trunk opening. Third, the operator rotated the boom arm to guide the suspended wheelchair into the cargo compartment along the lifting assembly's radial path. Fourth, once the wheelchair reached its designated storage position, the operator pressed the downward-direction control button to lower the chassis until its base rested securely on the support platform.

The lifting sling remained under tension while the base was supported by the platform, establishing a two-point support arrangement intended to prevent lateral sliding or tilting during vehicle movement. To unload any of the three wheelchair types, the operator followed the loading procedure in reverse: raising the wheelchair slightly from the trunk support platform using the electric winch, rotating the boom arm outward beyond the rear bumper, lowering the wheelchair vertically to ground level using the remote-control unit, and finally detaching the quick-release lifting sling.

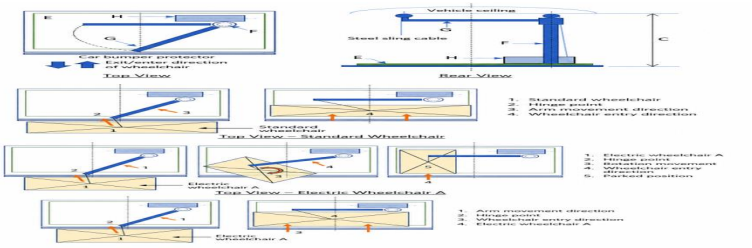




Figure 14. Steps for inserting an electric wheelchair Type B (a) and the corresponding loading sequence (b)

Ergonomic Postural Evaluation and Comparison

The introduction of the engineered electromechanical lifting aid changes the biomechanical demands placed on the helper during wheelchair loading and unloading. By replacing manual lifting forces with motor-driven vertical displacement, the system reduces the need for hazardous non-neutral postures, particularly trunk hyperextension, excessive forward flexion, and asymmetric lower-extremity bracing, which are associated with work-related musculoskeletal disorders (WMSDs) and lumbar spinal injuries. Tables 6 and 7 summarize the comparative postural sequences and physical activities performed by the helper before (manual mode) and after (assisted mode) implementation of the lifting device.

Table 6

Helper Postures When Loading the Wheelchair

Posture State	Task Activity (Manual)	Task Activity (Assisted)	Biomechanical Impact Reduction
Bending forward / trunk flexion	Reaching and securing a manual grip on the wheelchair frame	Attaching the quick-release sling harness to the wheelchair frame	Reduces static duration in trunk flexion
Standing upright (neutral)	Manually lifting the full wheelchair mass with both hands	Operating the handheld control unit to elevate the wheelchair via 12-V DC winch	Reduces static duration in trunk flexion
Severe backward trunk extension (~30°) & right leg abduction (~75°)	Supporting wheelchair weight against thigh/abdomen while stepping toward trunk threshold	Eliminated	Eliminates awkward bracing posture and spinal shear force (Ulrich, 2008)
Sustained awkward posture during forward locomotion	Advancing forward while balancing wheelchair mass against the body	Eliminated	Eliminates dynamic spinal loading and instability (Hart, 2012)
Standing upright (neutral)	Manually pushing wheelchair into cargo space	Guiding suspended wheelchair into cargo space via boom rotation and pressing lower button	Replaces heavy manual effort with low-force directional guidance (Hryciów, 2022)

Table 7
Helper Postures When Unloading the Wheelchair

Posture State	Task Activity (Manual)	Task Activity (Assisted)	Biomechanical Impact Reduction
Standing upright (neutral)	Reaching into trunk compartment and manually pulling wheelchair toward platform edge	Swiveling boom arm outward and guiding suspended wheelchair toward trunk threshold	Maintains neutral upper-body alignment; minimizes spinal traction (Abd Rahman et al., 2011; Miyawaki et al., 2012)
Asymmetric leg positioning & body bracing	Pulling wheelchair close to torso and supporting mass against thigh and abdomen	Eliminated	Eliminates body-contact impact and high static muscle load (Sydor et al., 2023)
Backward trunk extension (~30°) & leg abduction (~75°) during backward step	Holding wheelchair firmly against torso while stepping backward past trunk threshold	Eliminated	Eliminates severe spinal hyperextension during dynamic load descent (Haubert et al., 2015)
Sustained trunk flexion during lowering	Slowly lowering wheelchair mass to ground level while absorbing descending momentum	Operating handheld control unit with one hand to lower wheelchair while guiding frame with the other	Reduces asymmetric trunk rotation and high eccentric muscular strain during load positioning (Tang et al., 2018)
Bending forward / slight trunk flexion	Releasing manual grip and positioning wheelchair on ground	Detaching sling harness from wheelchair frame	Eliminates sustained load holding during grounding phase (Miyawaki et al., 2012)

As demonstrated in Tables 6 and 7, the empirical trials indicate a substantial change in the helper's working posture following the integration of the assistive lifting device, with successful proof-of-concept operation demonstrated for all three wheelchair types. In the unassisted manual procedure, loading and unloading require sustained periods of non-neutral body alignment. In contrast, the assisted procedure allows the helper to maintain a more upright standing posture during the powered elevation phase, limiting physical involvement primarily to attaching and detaching the lifting sling, operating the handheld remote-control unit, and providing horizontal guidance when rotating the boom arm and positioning the load. The available test records do not document the number of repeated trials conducted for each wheelchair type. Therefore, the findings are reported as successful operation in the demonstrated test cases rather than as a statistically estimated success rate.

Discussion

The empirical trials indicate that, during unassisted handling, the helper adopts a severe backward trunk extension of approximately 30°, combined with right-leg abduction of approximately 75°, while physically supporting the wheelchair's entire mass, which reaches up to 28 kg for the motorized models, against the thigh and abdomen (Sydor et al., 2023). This combination of asymmetric load distribution and extreme joint positioning may generate substantial compressive and shear forces in the lumbar region, particularly around the L5/S1 intervertebral disc, thereby increasing biomechanical loading. By eliminating the need to support and balance the wheelchair against the torso, the assistive device reduces direct mechanical loading on the helper's thigh and abdominal region (Sydor et al., 2023). Furthermore, the two-

point support arrangement, which combines upper sling tension with support from the base platform, is intended to restrain the wheelchair after it has been lowered onto the platform, reducing the need for manual stabilization or additional securing maneuvers within the confined trunk compartment. These findings are consistent with previous biomechanical research indicating that powered lifting assistance can substantially reduce physical demands on the arms, shoulders, and back during single-person wheelchair transfers (Tang et al., 2018). The present study extends this research from general lifting-assistance applications to the more specific and comparatively underexplored task of loading wheelchairs into vehicle trunks, which has been identified as a potential source of caregiver lumbar discomfort.

The comparative postural evaluation indicates that the designed electric lifter supports the application of fundamental ergonomic principles, including ease of use, safety, and comfort (Nurmianto, 1996). By converting a physically demanding manual handling task into a motor-assisted operation, the system reduces exposure to several risk factors associated with work-related musculoskeletal disorders, potentially improving operator safety, physical comfort, and operational efficiency during mobility-equipment transportation.

The functional testing and postural evaluation indicate that the engineered electromechanical lifting aid achieves its primary design objective of reducing physical exertion and limiting exposure to high-risk biomechanical postures during wheelchair transfers. However, a comprehensive evaluation must also consider these ergonomic benefits in relation to structural limitations, electrical-system implications, and practical installation constraints (Ulrich, 2008). The primary strength of the developed lifting aid lies in its human-centered engineering approach and relatively simple structural configuration (Wickens, 2004). By automating the vertical lifting and lowering phases, the device reduces the need for extreme lumbar extension (approximately 30°) and asymmetric lower-extremity bracing (approximately 75°), potentially reducing caregivers' exposure to risk factors associated with work-related musculoskeletal disorders (Rahman et al., 2023).

The system successfully accommodated different wheelchair configurations, including standard manual models (17 kg) and motorized electric models weighing up to 28 kg, within the nominal 100-kg rated capacity of the winch (Rahman et al., 2023). Based on platform development strategies Ulrich (2008), the device uses commercially available materials and standardized components, including a 6-cm hollow steel column, a 7-mm-thick structural steel plate, and a standard 12-V DC electric winch. These components facilitate fabrication and maintenance without requiring specialized proprietary parts. In addition, the two-point support arrangement, combining upper sling tension with base-platform support, is intended to limit displacement and tipping during vehicle transportation (Miyawaki et al., 2012).

Despite these functional benefits, several technical and spatial trade-offs must be acknowledged. Permanent installation of the support base and vertical column within the trunk compartment reduces the available luggage volume and may restrict the folding or use of third-row passenger seats in MPV platforms. The structural column height (90 cm) and boom arm length (55 cm) were specifically selected to accommodate the internal dimensions of the Toyota Avanza platform (Ulrich, 2008). Consequently, the device cannot be installed directly in all vehicle types without prior spatial assessment and dimensional redesign. Furthermore, because the lifting mechanism relies on the vehicle's 12-V DC electrical system, frequent operation while the engine is switched off may deplete the vehicle's primary battery and potentially cause voltage drops that affect other electrical systems. To ensure safe deployment and structural integrity during commercial or customized retrofitting, several practical implementation requirements must also be considered (Pahl et al., 2007).

Installation should be performed by qualified automotive electrical technicians to ensure appropriate wiring, fuse ratings, and relay integration and to prevent short circuits or electrical overloads in the vehicle's main wiring harness. Structural anchoring through welding and bolted connections must be performed appropriately on suitable structural floor members to withstand dynamic vibrational loads during vehicle operation (Miyawaki et al., 2012). For installation in vehicle models other than the reference Toyota Avanza, a preliminary spatial feasibility assessment must be conducted to adjust the boom arm length, column height, and rotational range to accommodate different tailgate mechanisms and trunk thresholds (Ulrich, 2008).

Within the international literature on wheelchair–vehicle interaction, these findings extend a research tradition spanning several decades and national contexts, from early rooftop wheelchair-loading concepts developed for the North American passenger-car market Klein (1985) to frontal-impact sled testing of wheelchairs used as vehicle seats in the United States Bertocci et al. (2001), Japanese evaluations of powered wheelchair lifts for motor vehicles Miyawaki et al. (2012), European occupant-safety analyses of wheelchair users in motor vehicles Hryciów (2022), and recent Polish and Slovak experimental studies of person–wheelchair–vehicle interactions (Sydor et al., 2023). Whereas much of this previous research has evaluated existing commercial lifting mechanisms, safety standards, or general biomechanical exposure during transfer operations Tang et al. (2018), the present study contributes a relatively low-cost retrofit design using commercially available components, specifically engineered for a widely used Southeast Asian MPV platform. It also provides functional testing involving three wheelchair configurations and a direct before-and-after comparison of observed working postures. In this respect, the study offers researchers and practitioners in other developing-country automotive markets, where specialized commercial wheelchair lifts may remain scarce and expensive Madej et al. (2023), an engineering and ergonomic evaluation framework for adapting similar assistive retrofits to locally prevalent vehicle platforms.

This study has several limitations that should be acknowledged. First, functional and postural evaluations were conducted using a single reference vehicle platform (Toyota Avanza) and a limited selection of representative wheelchair models. Therefore, the applicability of the specific structural dimensions to other vehicle body types and wheelchair geometries requires further validation and, in most cases, dimensional redesign. Second, the ergonomic evaluation relied on observational postural-angle estimates and comparative task descriptions rather than instrumented biomechanical measurements, such as electromyography or force-plate analysis. Consequently, although the observed postural changes are consistent with established biomechanical evidence regarding potentially hazardous exposure, the magnitude of spinal-load reduction was not directly quantified. Third, reliance on the vehicle's own 12-V electrical system introduces a practical operational constraint because of the potential for battery depletion during engine-off operation. Although this risk was identified, it was not experimentally evaluated under repeated operating cycles. Fourth, the number of repeated loading and unloading cycles for each wheelchair type was not documented, and the characteristics of the participating helper were incompletely reported. These limitations constrain conclusions regarding system reliability, operator variability, and safety beyond the demonstrated proof-of-concept tasks.

CONCLUSION

This study developed and evaluated, through proof-of-concept trials, an electromechanical assistive lifting device designed to facilitate wheelchair transfer operations in passenger vehicles, specifically adapted for the Toyota Avanza MPV platform. The engineered system incorporates a 12-V DC electric winch, a 7-mm-thick reinforced base plate, and a 360° rotatable boom arm with a two-point support arrangement for wheelchair positioning during transportation. Functional evaluations involving three distinct wheelchair configurations—standard manual wheelchairs, Type A front-folding electric wheelchairs, and Type B lateral-folding electric wheelchairs—demonstrated successful proof-of-concept operation across all three tested configurations. By automating vertical displacement, the device changes the caregiver's role during the demonstrated tasks from high-force manual lifting to lower-force rotational guidance and remote-control operation. The available test records do not document repeated trial counts for each wheelchair type; therefore, the results are reported as successful operation in the demonstrated test cases rather than as a statistically estimated success rate.

The study's principal contribution lies in integrating a human-centered lifting concept with the spatial constraints of a commonly used MPV platform through commercially available electromechanical components. During the observed task demonstrations, the device reduced the need for severe backward trunk extension and asymmetric lower-extremity bracing by transferring the vertical lifting function to the winch mechanism and limiting the helper's involvement primarily to attachment, control, and horizontal guidance. These findings support the technical feasibility of the proposed design as a caregiver-assistance retrofit. However, they

do not establish the elimination of injury risk, a direct reduction in spinal forces, or an improvement in quality of life, as these outcomes were not measured instrumentally or longitudinally.

Building on the limitations identified above, future research should focus on developing a quick-release modular frame and a telescoping boom mechanism to minimize intrusion into the cargo compartment, preserve passenger-seat folding functionality, and enable spatial adjustment across different vehicle body types beyond the reference MPV platform. Furthermore, integrating an intelligent electrical management system featuring dedicated auxiliary-battery isolation and automatic current-sensing cutoff protection should be explored to prevent depletion of the vehicle's primary battery and improve long-term electrical safety. Future studies should also incorporate instrumented biomechanical assessments, such as electromyography, to directly quantify changes in muscular activity and spinal loading associated with the use of the proposed lifting device.

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AUTHOR CONTRIBUTION STATEMENT

Wawan Yudiantyo: conceptualization, design, methodology, writing – original draft. Andrijanto: engineering design, testing, formal analysis. Christina Wirawan: supervision, validation, writing – review and editing. All authors read and approved the final manuscript.

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