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ORIGINAL ARTICLE

A Biomechanical Analysis of Caregiver Assisted Wheelchair to Car Transfers

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ABSTRAK

Tekanan biomekanikal yang dialami oleh penjaga semasa pemindahan pesakit ke dalam kereta, dengan dan tanpa prototaip pengangkat yang diubah suai, telah dinilai. Oleh kerana ruang yang terhad, pemindahan pesakit dengan masalah mobiliti ke kereta adalah berisiko kepada penjaga mereka. Kajian ini bertujuan untuk mengukur pengaktifan otot dan beban pada tulang belakang semasa pemindahan dari kerusi roda ke kereta, dengan membandingkan kaedah pemindahan manual dengan prototaip pengangkat yang diubah suai. Pengaktifan otot pada lapan otot utama diukur dengan menggunakan elektromiografi permukaan, manakala beban lumbar pada cakera L5/S1 dinilai menggunakan penjejakan pergerakan seluruh badan dan plat daya. Seramai 13 peserta terlibat dalam kajian ini. Analisis Kovarians (ANCOVA) menunjukkan bahawa berat pesakit mempunyai kesan signifikan terhadap beban lumbar, manakala pengalaman dan ketinggian penjaga tidak. Setelah pelarasan berat pesakit, purata daya mampatan paksi puncak dan daya ricih anterior-posterior) didapati menurun dengan ketara apabila menggunakan prototaip pengangkat (kedua-dua $p < 0.001$). Selain itu, penggunaan prototaip pengangkat menunjukkan pengurangan signifikan dalam pengaktifan otot erektor spinae longissimus kiri ($p<0.001$), erector spinae longissimus kanan ($p=0.028$), deltoid anterior kiri ($p=0.007$) dan biseps brakii kiri ($p=0.003$). Kajian ini menyediakan penilaian biomekanikal pertama bagi pemindahan pesakit ke dalam kereta dari sudut penjaga, sekali gus menunjukkan beban tinggi yang dialami. Pengurangan yang signifikan dalam kedua-dua beban lumbar dan pengaktifan otot dengan penggunaan prototaip pengangkat membuktikan bahawa intervensi yang lebih baik diperlukan untuk menjadikan proses ini lebih selamat bagi semua pihak yang terlibat.

Kata kunci: *Analisis biomekanik; pemindahan kereta; pencegahan kecederaan; pengendalian pesakit*

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ABSTRACT

Car transfers for patients with mobility impairments are risky for caregivers due to constrained spaces and high biomechanical stresses. This study aimed to measure muscle activations and spine loads comparing the manual transfer method with a modified lifter prototype. Muscle activations at eight key muscles using surface electromyography and lumbar loads at the L5/S1 disk using full-body motion tracking, and force plates were evaluated. A total of 13 participants took part in the study. An Analysis of Covariance (ANCOVA) showed that patient weight significantly influenced lumbar loads while caregiver experience and height did not. After adjusting for patient weight, average peak axial compression forces and anterior-posterior (AP) shear forces were significantly lower when the lifter prototype was used (both $p < 0.001$). Significant reductions in muscle activations were also found with the lifter prototype for the left and right erector spinae longissimus ($p < 0.001$ and $p = 0.028$, respectively), left anterior deltoid ($p = 0.007$) and left biceps brachii ($p = 0.003$). This study provides the first biomechanical evaluation of car transfers on caregiver, highlighting the high loads experienced. The significant reductions in both lumbar loads and muscle activations with the prototype lifter prove that better interventions are needed to make this process safer for all parties involved.

Keywords: Biomechanical analysis; car transfer; injury prevention; patient handling

INTRODUCTION

Musculoskeletal disorders are a pressing issue in today's society with approximately 1.3 billion cases reported and 138.7 million disability-adjusted life years lost in the year 2017 alone (Safiri et al. 2021). Worldwide, nurses are among the highest at risk of developing work-related musculoskeletal disorders (WMSDs) with studies reporting prevalence numbers ranging from 60-90% (Krishnan et al. 2021; Nguyen et al. 2020; Passali et al. 2018; Sun et al. 2023). This is in line with the U.S. Bureau of Labor Statistics (2020) which found that the health care and social assistance sector reported the most WMSD cases in the private sector in 2018. The Center for Disease Control and Prevention (CDC) states that frequent patient handling which involves manual lifting, repositioning and moving of patients is the single most significant risk factor for overexertion injuries in healthcare workers (National Institute for Occupational Safety and Health 2023).

Informal caregivers, often family members or friends, are integral to the well-being and independence of the elderly or those with mobility challenges. In low- and middle-income nations, the informal caregiver plays an important role in filling the shortage of healthcare workers without receiving the necessary recognition and thus the training and education to perform their role (Hogan et al. 2022). Informal caregivers are known to face physical and emotional distress due to caregiving (Bom et al. 2019; Del-Pino-Casado et al. 2021). These factors show the importance of lessening the burden of caregiving on the informal caregivers. Assistive devices have been shown to bring positive impact to hospitals but there is a lack of studies on the effect of such devices on informal caregivers (Marasinghe et al. 2022). One of the patient-handling task carried out by both formal and informal caregivers is car transfers.

Moving a patient from a wheelchair to a car seat or vice versa (car transfers), usually with the assistance of another person or a device is a common activity in hospitals and care homes when arranging for periodical health check-ups or non-emergency transfers. Environmental factors, such as the presence of uneven or sloped terrain where the car is parked, makes car transfer a more difficult challenge than indoor sitting transfers (Barbareschi & Holloway 2020). The limited space around a car compared to indoor situations also attributes to the increased difficulty of this type of transfer. This could pose a greater risk to caregivers in developing WMSDs.

To the best of our knowledge, no studies were found to measure the frequency of car transfers handled by caregivers and the impact on their well-being. However, the increase in the need for attention in car transfers is apparent as a lot of nations are heading towards an aging society and the fact that more people are choosing to use private vehicles for transport (Mohd Rosnu et al. 2023). Efficient transfer in and out of private vehicles will go a long way in helping the mobility impaired and the elderly get access to the facilities they need. In this study, we investigate the effect of an intervention on the car transfer task. It is well known that for other patient handling tasks, intervention studies already exist, such as for lateral bed transfers and bed to wheelchair transfers (Abdul Halim et al. 2022; Law et al. 2022a; Law et al. 2022b). Biomechanical studies of such transfers give valuable insight on how to address these problems through quantitative means (Budarick et al. 2020; Hwang et al. 2020; Riccoboni et al. 2021; Wiggermann et al. 2021; Zhou & Wiggermann 2021).

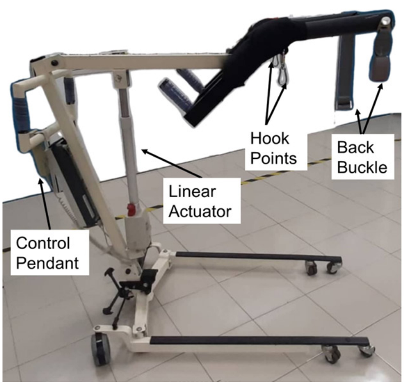
Despite the availability of various car transfer aids, such as car transfer slide sheets, swivel cushions and assistance straps/handles, these passive devices still necessitate lifting by the caregivers or a high degree of self-sufficiency from patients (Ferri n.d.). While wheelchair accessible vehicles present an alternative solution, they are inaccessible to low-income populations. There are a handful of mechanical powered solutions available in the market such as the Hoyer Advance (Joerns Healthcare 2023), BestLift Patient Lift (Ferri 2023) and the Milford Person Lift (Autochair n.d.). However, based on our review of the literature, we did not identify any studies that specifically measured the efficacy of these interventions for car transfers. In this study, we used a modified floor lift (NEAR-1) and investigated its effects on the caregivers' body during car transfers. More details on the design and usage of the NEAR-1 lifter prototype can be found in the paper of 4Abdul Halim et al. (2023).

This study aimed to examine the biomechanical effects of transferring patients into and out of a small car, both manual and with the assistance of a lifter prototype (NEAR-1, Figure 1). Specifically, it sought to quantify and compare axial compression and AP shear forces at the L5/S1 spinal disc, as well as muscle activity across eight muscle groups. These measures were used to evaluate the physical strain placed on caregivers during manual transfers versus those performed using the lifter. Additionally, the study investigated whether patient-handling experience (formal vs. informal caregivers) influenced these biomechanical outcomes.

MATERIALS AND METHODS

Demographic

This study was carried out in a laboratory in Universiti Sains Malaysia (USM). Ethics approval



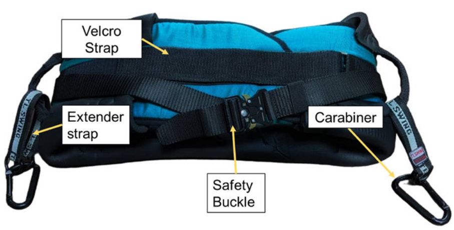


FIGURE 1: NEAR-1 lifter prototype and thigh strap

from the Human Research Ethics Committee of USM (JEPeM) (20080447) was obtained prior to carrying out this study.

A total of 13 participants took part in this experiment. The participants consisted of seven female registered nurses (formal caregivers) from the Advanced Medical and Dental Institute (AMDI) and six male students (informal caregivers) from USM Engineering Campus. The sample size was determined using power analysis in the G*Power software for windows (Kang 2021). The effect size of 1.18 was calculated from the peak compression force data of manual transfer group and sit to stand lift group for the bed to wheelchair transfer activity in Daynard et al. (2001). This effect size was chosen for our sample size calculation because there are no exact car transfer intervention studies available in the literature. However, the selected study is comparable to ours as it involves a sitting-to-sitting transfer, specifically from a bed to a wheelchair, using both manual methods and an intervention (sit-to-stand lift). Similarly, our study investigated car transfers performed manually and with a modified lifter as an intervention. A minimum sample size of ten was determined for both a matched pair one tailed t-test and Wilcoxon sign ranked test ($\alpha = 0.05$, $1-\beta = 0.95$), indicating 13 (the number in this study) as being a suitable sample size. The chosen sample size was also consistent with other similar patient transfer studies (Cheung et al. 2020; Riccoboni et al. 2021; Wiggermann et al. 2021). The nurses recruited were to represent formal caregivers who had received formal training in patient handling. The students allowed us to represent the informal caregiver population conducting car transfers with a short period of training, not dissimilar to someone who took care of their mobility impaired family member or friend without the help of a trained healthcare worker.

All participants were informed of the study procedures and provided written informed consent prior to participation. Inclusion criteria required participants to be under the age of 60, weigh less than 110 kg, and had no history of back injuries or physical limitations that could affect movement or lifting capacity. These criteria were selected to minimise potential harm to participants during patient transfer tasks and to ensure biomechanical data accuracy. Exclusion criteria included individuals with musculoskeletal, neurological or cardiovascular conditions that could compromise safety or influence movement patterns, as well as those who were pregnant or taking medications that might affect neuromuscular control or physical performance. Individuals unable to provide informed consent, such as due to cognitive or language barriers were also excluded. Participants were recruited through convenience sampling, based on the availability of nurses and students, which allowed for efficient data collection while acknowledging limitations in generalisability. Due to only female nurses being available as experienced subjects, all students chosen for the experiment were male. Table 1 showed demographic statistics. As a reference, the average Malaysian height for men and women was 166.8 cm and 157.6 cm, respectively. Whereas the average weight was 70.7 kg for men and 62.3 kg for women (Chia et al. 2023).

Materials Used

(i) Lifter prototype (NEAR-1)

The lifter prototype used the base from a commercially available floor lift with a modified arm section to be lower and carried patients below their arms. The device forwent the use of a full body sling for a thigh strap for easier inserting and

TABLE 1: Subject demographic

Demographic	**Mean (SD)**	
	Male (n=6)	**Female (n=7)**
Age (years)	33.17 (8.38)	41.29 (9.79)
Weight (kg)	79.81 (12.95)	72.3(17.90)
Height (cm)	171.7 (7.50)	156.84(6.15)
Experience, for registered nurses (years)	-	19.14 (8.67)

did not have a rotating joint where the patient can freely swing while being moved in the machine. The prototype lifter was designed to allow for all seated transfers including into and out of vehicles. However, the machine was limited in its use to patients who were conscious with upper body strength (enough to maintain a sitting position throughout the transfer procedure).

(ii) Sensors

This study employed motion tracking, ground reaction force (GRF) measurement and muscle activity measurements. An inertial motion capture system, the Xsens MVN Awinda wireless motion tracker (60Hz), was used to track motion. GRFs were measured with a force plate (Bertec Corp, Type AM6500 Amplifier, 500Hz down sampled to 60Hz). These were the inputs for the musculoskeletal modelling.

Muscle activations of eight muscle groups were measured with bipolar surface electromyography (EMG) using disposable pre-gelled electrodes (Kendall Medi-Trace 200, Cardinal Health, Australia) connected to Shimmer3 EMG units (Realtime Technologies Ltd., Ireland, 60Hz). These units transmitted data via Bluetooth to a PC for collection using the iMotions 9.0 platform (iMotions, Copenhagen, Denmark). The measured muscle groups included the left and right upper trapezii (UT_{left}, UT_{right}), biceps brachii (BB_{left}, BB_{right}), anterior deltoids (AD_{left}, AD_{right}) and the longissimus erector spinae (ES_{left}, ES_{right}). The placement of EMG electrodes adhered to the SENIAM guidelines (SENIAM Project 2005). Prior to electrode placement, the designated locations were cleaned with alcohol and allowed to dry (Boettcher et al. 2008; Hardie et al. 2015).

Experimental Procedure

Both groups (formal and informal caregivers) underwent training in using the lifter prototype. They were instructed on applying the sling, attaching buckles and hooks, and operating the lifting and lowering of the arm through the control pendant. The informal caregiver group received supplementary training on manual patient handling during vehicle transfers. This consisted of watching a video demonstration of transfers performed by formal caregivers (nurses). Participants (subjects) took turns as both the patient and caregiver, with two individuals participating in each session. During each session, one subject acted as the caregiver while the other assumed the role of the patient. For example, on Day 1, two caregivers (Subject 1 and Subject 2) attended, with Subject 1 performing the caregiver role and Subject 2 the patient role. On Day 2, the same pair returned with their roles reversed hence, every subject plays the role of patient and caregiver once each. Only one subject was unable to complete both roles and withdrew after serving solely as the caregiver. To address this dropout, another subject was required to play the patient role twice. This approach followed a protocol similar to that described by Riccoboni et al. (2021). Table 1 showed the demographic of the participants who took part in the study. When assuming the patient's role, a knee restraint was applied to a randomly selected leg. This measure aimed to lessen the caregiver's aid during the transfer, simulating the handling of a partially impaired patient. With the patient's leg securely immobilised at a slightly bent angle, their ability to support themselves on that leg was compromised, consequently reducing the level of assistance available to the caregiver.

Caregivers transferred patients in and out of a car using both manual and lifter methods (Figure 2). The transfers were conducted between the rear seat of a small subcompact hatchback and a wheelchair. The deliberate choice of a small car was based on its space restriction, creating a worst-case scenario, particularly as the doors did not open very widely.

Maximum voluntary isometric contraction (MVIC) tests were carried out as followed: (a) BB_{left} and BB_{right}; lying flat on back with a strap attached to the forearm (hand kept at 90°) and the bed frame to provide resistance, (b) ES_{left} and ES_{right}; lying face down on the bed and lifting arms and feet off the bed surface forming a dish shape (Hardie et al. 2015), (c) AD_{left}, AD_{right}, UT_{left} and

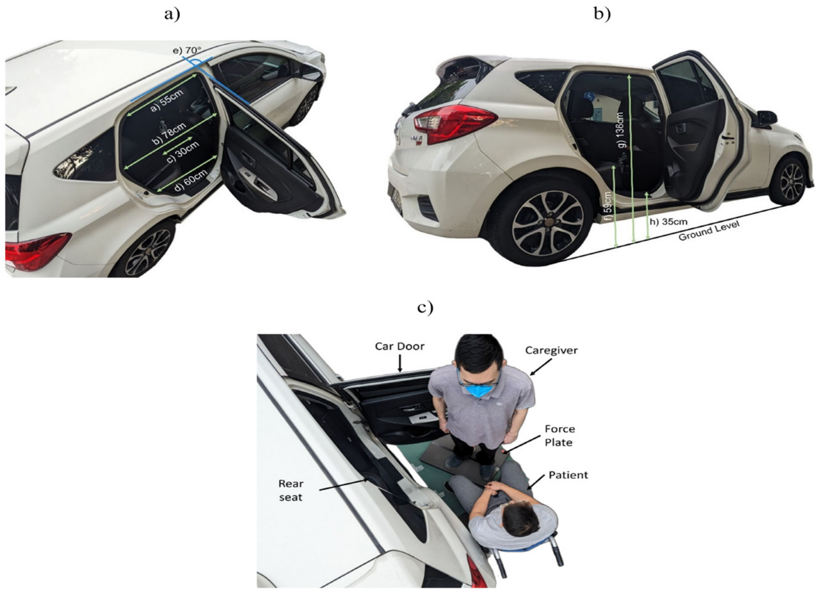


FIGURE 2: (a) and (b) Rear door opening dimensions of the car; (c) top view of patient and caregiver position for manual transfer

UT_{right}; Elbow extended with shoulder abducted 90° in plane of scapula while resistance was applied at wrist ("empty can" test) (Boettcher et al. 2008). Next, the participants were required to calibrate the motion tracking setup according to the Xsens software.

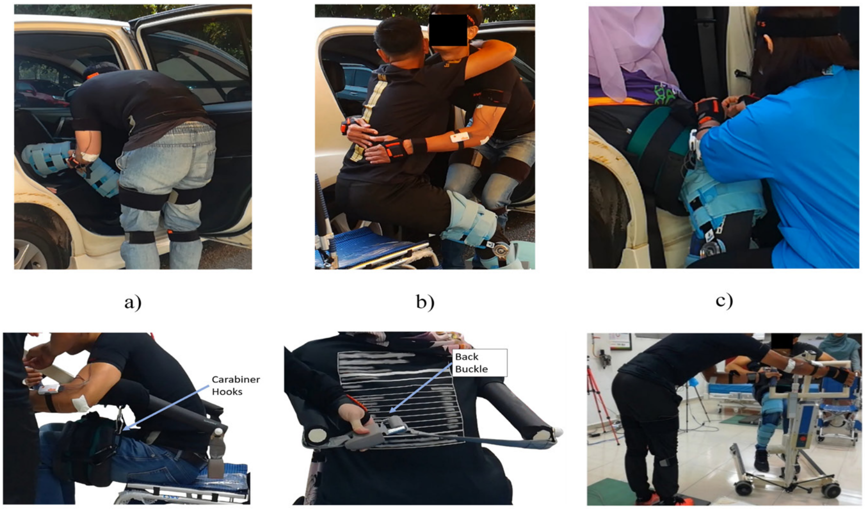
Figure 3 showed the overall process of using the powered lifter where (c) the patient shuffled while remaining seated to the edge of the car seat where the caregiver squatted to apply the thigh strap. The thigh strap was then tightened and fastened with a buckle and Velcro, (d) the caregiver then connected the thigh strap to the lifter via carabiner hooks on extender straps on two points (left and right), and (e) a back support was connected behind the patient using seat belt buckles as a safety measure. The linear actuator was then extended to lift the patient off the car seat and transferred to the wheelchair where the patient was lowered, and all the buckles removed. The sling then was removed from the patient. This entire process was repeated to move the patient from the wheelchair into the car. The transfers were broken down into subtasks for each caregiver to carry out. The exact subtasks carried out are shown in

As shown Table 2, ach caregiver carried out both manual and lifter transfers twice for redundancy in case of data loss due to wireless transmission issues.

Data Analysis

(i) Lumbar loads

Musculoskeletal modelling was conducted using AnyBody modelling system 7.4 (AnyBody Technology, Aalborg, Denmark) (Bassani et al. 2017). Joint reaction forces were obtained via inverse dynamics calculations with muscle recruitment and external forces in a bottom-up approach using the full body musculoskeletal modelling tool. The Inertial MoCap example model (incorporated with Xsens) contained in the AnyBody Model Repository was adapted to use for this study (AMMR 2024) with modifications made for use of external ground reaction forces measured using the force platforms (Figure 4). The



a) b) c)

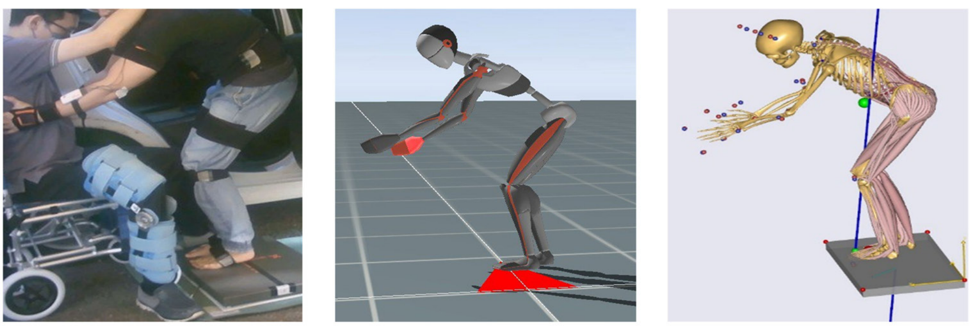
d) e) f)

FIGURE 3: Subtasks performed for this experiment (a) turn legs, (b) manual-transfer, (c) lifter-fasten thigh strap, (d) lifter – hook thigh strap, (e) lifter – fasten back buckle, (f) lifter-transport

TABLE 2: Transfer subtasks

Transfer Type	**Manual Transfer**	**Lifter Transfer**
Transfer subtask	Turn patient legs from inside the car to the edge * Transfer patient from car seat to wheelchair*	Turn patient legs from inside the car to the edge* Fasten thigh strap* Hook thigh strap to lifter* Fasten back buckle* Move patient to wheelchair Unfasten back buckle Unhook thigh strap Unfasten thigh strap Transport*

*subtasks included in biomechanical analysis.
The steps were reversed when transferring from wheelchair-to-car



a) **b)** **c)**

FIGURE 4: (a) Recording of transfer; (b) xsens avatar; (c) inverse dynamics processing in AnyBody

joint reaction forces analysed in this study were the axial compression and anterior-posterior (AP) shear forces at the L5/S1 disk.

(ii) Muscle activations

Raw EMG values from the experiment were passed through a fourth-order, zero-phase-lag bandpass Butterworth filter with a high pass cut-off frequency of 20Hz and low pass cut off frequency of 511Hz (van Boxtel 2001). A 50Hz band stop filter was used to eliminate line noise (Bokil et al. 2010; Widmann et al. 2015). A linear envelope was produced through full wave rectification (Lajante et al. 2017) and a low pass filter of 10Hz (van Boxtel 2001).

The study involved measuring muscle activation signals from participants using surface EMG as they performed different subtasks involved in both manual and lifter transfers. To make these measurements comparable across individuals, the raw EMG signals collected during these subtasks were normalised. This normalisation process used data obtained during MVIC tests conducted for each specific muscle group prior to the transfer tasks. During MVIC tests, participants contracted a muscle as strongly as possible against resistance, establishing a baseline representing that muscle's peak activation capacity. The muscle activation signals recorded during the transfer subtasks were then expressed as a percentage of this peak MVIC value, resulting in data measured in percentage of Maximum Voluntary Contraction (%MVC). This %MVC represented the relative effort a muscle exerted during a specific subtask compared to its maximum potential. To get a robust measure of the sustained or frequently high muscle activity during the entire transfer process, the 90^{th} percentile %MVC was calculated for each muscle group across all the relevant subtasks performed for both the manual and lifter transfer methods. The 90th percentile was the value below which 90% of the %MVC data points fall, providing a good indicator of the higher-end muscle loading experienced during the task (Hwang et al. 2019). Finally, these 90^{th} percentile %MVC values were statistically compared between the manual and lifter transfers for each muscle to determine the impact of the lifter on muscle effort.

Statistical Analysis

All statistical tests were carried out using the statsmodels package in python 3.10 with an alpha level of 0.05. An Analysis of Covariance (ANCOVA) analysis was conducted to investigate the effect of transfer method, patient weight and caregiver type on both lumbar loads.

Muscle activation data was analysed by comparing 90^{th} percentile values for all muscles in all subjects. Normality of each group was first tested using the Shapiro-Wilks test. ES_{left} and BB_{right} muscles were tested with paired-sample T-tests. The ES_{right} and AD_{left} muscles were tested using the non-parametric related-samples Wilcoxon signed rank test (violation of normality, symmetrical distribution of differences) whereas the rest were tested using the related-samples sign test (violation of normality, asymmetrical distribution of differences).

Left and right muscle activations were tested using a one sample t-test (null hypothesis: the difference in activation between the left and right muscles was 0; $p \leq 0.05$ = asymmetric, $p > 0.05$ = symmetric).

RESULTS

Lumbar Loads

The average lumbar loads were plotted with error bands (one standard deviation) for each subtask arranged in the order in which the caregivers performed them. These tasked were time-averaged and plotted (Figure 5). Medio-lateral shear values were not considered in the analysis from this point forward as they were very low and had very little variance between tasks and subjects. 'Lifter transport' was a subtask which was not included in the figure because it was carried out separately to investigate the forces required to move the prototype lifter around (pushing, pulling, turning left and turning right;

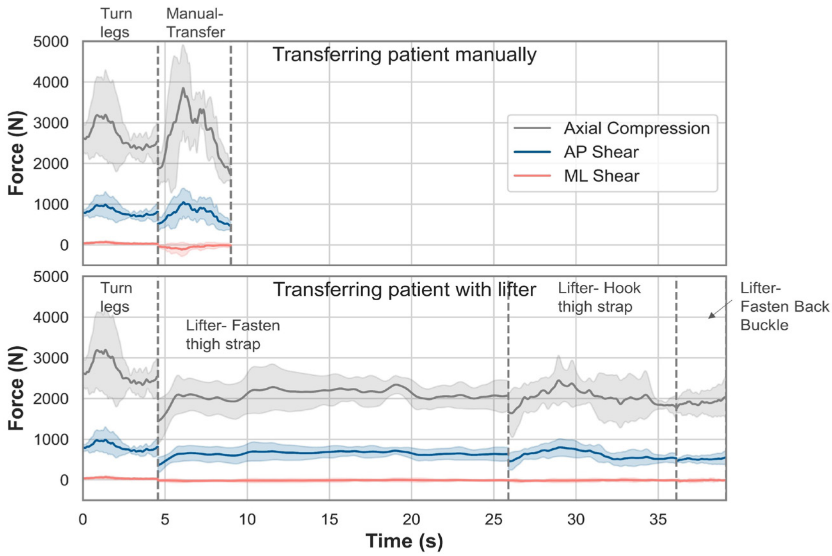


FIGURE 5: Lumbar loads against average time

longer time and more actions overall) thus, not representative of moving the patient to and from the car seat to the wheelchair. This subtask was included in all the following lumbar load analyses except not being displayed in Figure 5. All analysis relating to lumbar loads only consisted of 12 subjects (six formal caregivers, six informal caregivers) as data from one subject was of poor quality.

A repeated measures ANCOVA was conducted to examine how patient weight, caregiver height and caregiver type (representing experience) influenced the peak axial compression and anterior-posterior (AP) shear forces experienced at the L5/S1 spinal joint during transfers. The analysis showed that neither caregiver height nor caregiver experience had a significant impact on these measured lumbar loads. However, patient weight was found to have a significant effect on AP shear forces and an almost significant effect on axial compression forces (Table 3). Consequently, the comparison between manual and lifter transfers was re-analysed adjusting for the average patient weight (69.19 kg). This adjusted analysis revealed a significant reduction in overall mean peak axial compression forces when using the lifter prototype, compared to the manual method as seen in Figure 6 and Table 4. For overall mean peak AP shear forces, a significant reduction with the lifter was evident only after adjusting for patient weight.

When assessed against safety standards, the study found that only the manual transfer exceeded the National Institute for Occupational Safety and Health (NIOSH) action limit of 3400N for lumbar compression forces. However, the

TABLE 3: Tests of between-subjects effects

Source	Measure	p-value
Patient weight	Axial compression	0.055
	AP shear	0.016*
Caregiver height	Axial compression	0.142
	AP shear	0.070
Participant type (caregiver experience)	Axial compression	0.659
	AP shear	0.300

*significant at $p < 0.05$

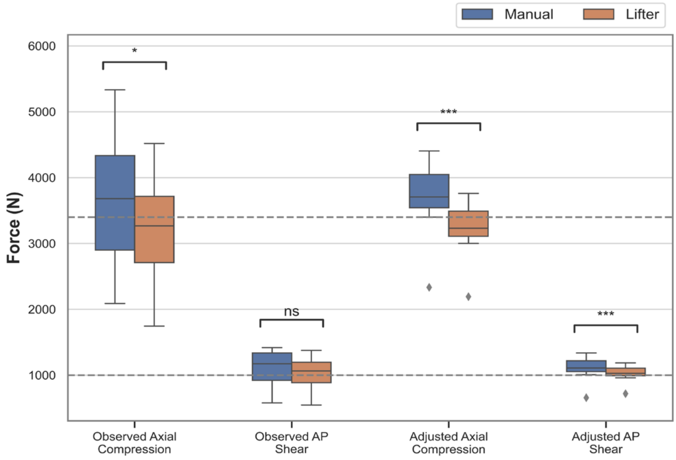


FIGURE 6: Overall mean peak lumbar loads. (ns: not significant, *: p <0.05, **: p <0.01 ***: p <0.001,

TABLE 4: Descriptive statistics of spine load measures during both tasks adjusting for patient weight

	Method	Mean (SD), N	p-value
Axial Compression	Manual	3716.84 (960.17)	<0.001*
	Lifter	3240.57 (837.58)	
AP Shear	Manual	1111.45 (267.76)	<0.001*
	Lifter	1031.26 (249.24)	
*significant at p < 0.05			

commonly used limit of 1000N for AP shear forces (Gallagher & Marras 2012) was exceeded by both the manual and lifter transfer methods. Further details on the observed mean peak lumbar loads for specific subtasks were presented in Table 5.

Muscle Activation

A boxplot of the 90th percentile EMG reading of the arm and back muscles during the car transfer activity for the manual transfer and powered lifter were shown in Figure 7. Using the lifter, it reduced

TABLE 5: Mean peak lumbar loads (average of max values for each recording) at L5/S1 for manual and lifter prototype car transfers by subtask.

Load	Subtask					
	Turning legs	Manual-transfer	Lifter-Fasten Thigh Strap	Lifter-Hook Thigh Strap	Lifter-Fasten Back Buckle	Lifter-Transport
Mean Peak Axial Compression (SD), N	2729.91 (1156.72)	3477.81 (793.77)	2410.81 (485.20)	2601.27 (760.76)	1897.02 (377.21)	1545.25 (481.38)
Mean Peak AP Shear (SD), N	846.48 (378.43)	1059.9 (263.56)	756.76 (164.97)	810.79 (246.57)	534.71 (109.61)	431.94 (169.10)
Mean Peak ML Shear (SD), N	56.34 (35.29)	112.15 (64.01)	68.03 (15.13)	82.83 (50.90)	60.79 (38.66)	45.74 (18.11)

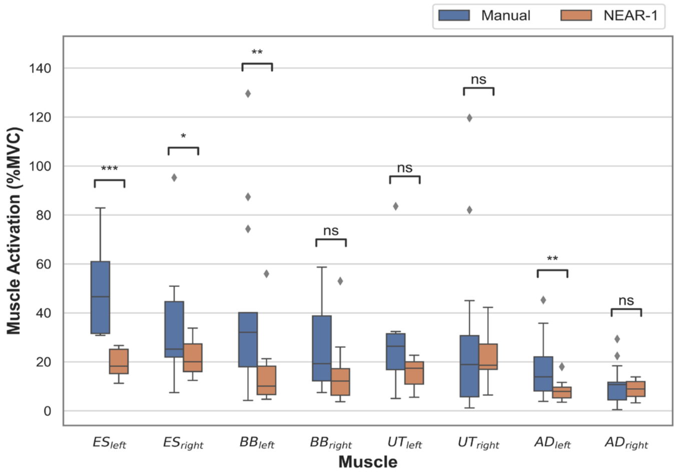


FIGURE 7: 90th percentile electromyography readings for each muscle during car transfer (ns: not significant, *: $p < 0.05$, **: $p < 0.01$ ***: $p < 0.001$)

muscle activation by half notably, for ES_{left} from 49.98% to 19.11% (p<0.001). The BB_{right} muscle showed a mean reduction of 10.63% (p = 0.064). Significant median reductions of 15.01% (p = 0.003) and 5.89% (p = 0.007) were also observed for the BB_{left} and AD_{left} muscles respectively. The ES_{right} muscle also showed a significant median reduction (3.65%, p = 0.028) in muscle activity when using the lifter compared to manual transfer. Median reductions when using the lifter were observed for the UT_{left} (8.06%, p = 0.092) and UT_{right} (3.48%, p = 0.581) muscles but were not significant at the chosen alpha level. Whereas the AD_{right} muscle was the only muscle to show a slight increase in median muscle activity (1.39% increase, p = 0.581) in this comparison.

Muscle activation asymmetry, evaluated as the difference in activity between the left and right sides of a muscle group, was assessed using one-sample t-tests to determine if activation patterns deviated significantly from symmetry ($p \leq 0.05$); seen in Figure 8. Results showed that during manual transfers, the erector spinae (ES) muscle group exhibited statistically significant asymmetry (Mean (M) = 16.10%, p = 0.003). The anterior deltoid (AD) and biceps brachii (BB) groups did not show statistically significant asymmetry (AD: M = 6.97%, p = 0.107; BB: M = 14.81%, p = 0.136). The upper trapezius (UT) group also demonstrated non-significant asymmetry during manual transfers (M = -3.11%, p = 0.189).

When comparing to lifter transfers, significant reductions in mean muscle asymmetry were observed for the ES group, shifting from asymmetric (M = 16.10%, p = 0.003) to symmetrical activation (M = -2.61%, p = 0.189). The AD and BB groups continued to show no statistically significant asymmetry with the lifter (AD: M = 0.06%, p = 0.956; BB: M = -0.23%, p = 0.893), maintaining a symmetrical pattern. However, the use of the lifter prototype led to an increase in mean muscle activation asymmetry in the UT group, which became statistically significant (M = -5.63%, p = 0.038) compared to the manual method (M = -3.11%, p = 0.189). Overall, only the ES muscle group positively changed from asymmetric to symmetrical activation with the lifter whereas the opposite was true for the UT group.

DISCUSSION

This study aimed to measure and compare spine loads and muscle activations experienced by caregivers during the process of car transfers with and without using the NEAR-1 prototype

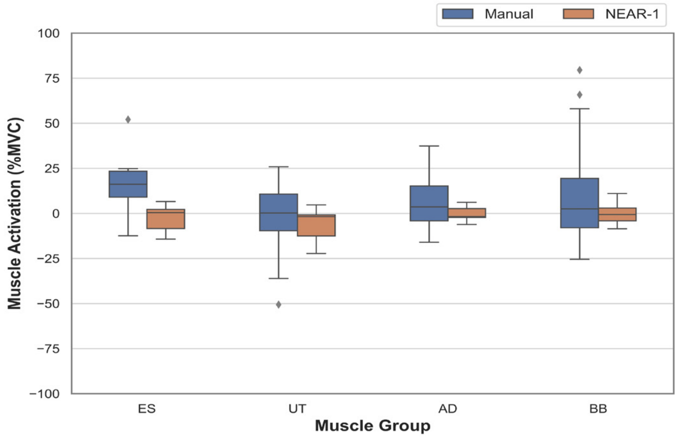


FIGURE 8: Average 90th percentile muscle activation (%MVC) difference between left and right muscles (left muscle - right muscle)

lifter. The parameters evaluated were the L5/S1 lumbar loads and the muscle activations in the lower back, shoulders as well as the upper arms. The transfers were carried out in two ways; the manual method and using the prototype lifter.

Lumbar Loads

Average peak axial compression and AP shear forces at the L5/S1 joint for manual patient transfer exceed the NIOSH recommendation of 3400N for compression and commonly used threshold of 1000N respectively (Gallagher & Marras 2012). These results are in line but slightly lower compared to previous studies carried out for similar sitting to sitting transfers by Owen and Garg (1991) (compression = 4795N, AP Shear = 954N) and Jäger et al. (2013) (compression = 5100N), of which the latter also used a 3D dynamic simulation method to obtain results. The slightly lower results in this study are possibly because of the space restriction during a car transfer causing some caregivers to hold on or push against the car as compensation strategies to maintain stability during transfer which reduces the spinal loads but could possibly increase the hand loads thus, increasing the risk of WMSDs at the hands and wrists which are also common among nurses (Almhdawi et al. 2021; Clari et al. 2019).

Analysing the descriptive statistics shown in Table 3, the lifter prototype shows a reduction in lumbar loads where the axial compression forces are now below the NIOSH limits of 3400N but remain above 3000N. This can be attributed to the action of turning the patients legs out of the car. It can be observed that the turning legs subtask shows a high average compression and shear force reading (Figure 5). The legs are a heavy body part, around 31-38% body weight (Dumas et al. 2007; Merrill et al. 2019), and thus put a large strain on the caregivers when lifted and turned. The higher than ideal shear values for the lifter could also be attributed to the frequent stooping and squatting required in the subtasks. Therefore, it can be noted that the task of turning the patients' legs is something that requires intervention to make car transfers safer. The use of a swivel seat could help to reduce the strain placed on the caregivers. However, further studies are required to confirm this hypothesis.

The ANCOVA analysis revealed that caregiver experience did not significantly impact the spine loads experienced during the transfers. While previous studies have demonstrated that experience is a significant factor influencing spine loads (Dutta et al. 2011), the variations in transfer activities, such as the type of transfer and sling used, likely account for this difference. This suggests that the lifter prototype used in this study may offer a safer alternative for less experienced caregivers.

Muscle Activations

This study investigated the effect of using the lifter prototype against manually transferring patients to and from a car rear seat to a wheelchair. EMG readings show a reduction in all muscle activations. ES_{left}, ES_{right}, AD_{left}, and BB_{left} and show a statistically significant reduction when comparing the lifter to the manual method during car transfers. Previous studies have shown that ES muscle activations are lowered when using assistive devices for lifting for bed to wheelchair transfers (Cheung et al. 2020) and other daily transfers carried out by caregivers (Vinstrup et al. 2020). Cheung et al. (2020) show that the ES muscles have high average activations (up to 78.77%) especially during the turning phase of the lifting of patients onto a wheelchair from bed. Our results in this study do not range that high even when using the 90^{th} percentile metric for %MVC. This could be due to methodological differences in the processing of the raw EMG signals and their omission of an MVIC test in favour of obtaining MVC values from the trials themselves. There are two outliers with more than a 100% MVC (BB_{left} and UT_{right} for manual transfer) which were not removed in the analysis. This is because the higher values in the EMG readings were found during the lifting and lowering steps of the manual transfer. Previous studies have shown that normalising against isometric tasks during the MVC test could lead to muscle activations above a 100% when the actual task is more dynamic in nature (Ball et al. 2013; Suydam et al. 2017). This points to large strains put on the muscles during those activities.

The observed differences in muscle activation asymmetry between the manual and lifter transfer methods warrant further discussion. Asymmetrical muscle activation can signify uneven loading and is a factor potentially increasing the risk of musculoskeletal disorders (Renkawitz et al. 2006). Therefore, reducing such asymmetry, particularly in vulnerable areas like the lower back, is a significant goal in injury prevention. A key finding is the mitigation of statistically significant asymmetry in the ES muscles when transitioning from manual transfer to using the lifter prototype, where activation becomes symmetrical. This improvement in lower back asymmetry is particularly noteworthy, given the high prevalence of back injuries among caregivers (Clari et al. 2021; Gilchrist Pokorná 2021; Latina et al. 2020). For the AD and BB muscles, activation remained largely symmetrical across both manual and lifter transfers with no statistically significant asymmetry observed. However, the use of the lifter prototype led to a statistically significant increase in activation asymmetry in the upper trapezius muscle group (mean difference = -5.63 %, $p = 0.038$), whereas this asymmetry was non-significant during manual transfer ($p = 0.189$).

While biomechanical effects in the lumbar spine and ES improved with the lifter, this unexpected asymmetry in the UT muscles deserves careful consideration. Asymmetrical UT activation is associated with scapular imbalance known to lead to altered shoulder mechanics and neck posture which are key contributors to shoulder pain and musculoskeletal pathology (Kong et al. 2023; Lucado 2011). Over time, such asymmetry might predispose caregivers to neck strain, upper crossed syndrome, and increased risk of WMSDs of the shoulder and cervical regions. Although lifter use significantly reduces lower-back loading, the trade-off may increase loading on the upper trapezius and cervical region. These findings suggest that future lifter designs and training protocols should aim to promote more symmetric shoulder activation. For instance, ergonomic adjustments to strap placement, lifter arm height, or caregiver posture and exercise (Villanueva et al. 2020) may help to mitigate UT asymmetry. Overall, while the lifter delivers clear lower-back biomechanical benefits, the apparent increase in UT asymmetry highlights a potential upper-shoulder cost that must be addressed before recommending widespread clinical or home use.

The NEAR-1 lifter prototype was also qualitatively evaluated through perceived workload and usability questionnaires (Abdul Halim et al. 2023). The device was shown to be quite favourable among the caregivers (n = 51) compared to other methods of patient transfer such a walking belts and mobile hoists by obtaining both high usability scores and low perceived workloads.

Limitations of Device and Experimental Protocol

A potential explanation for the low lumbar loads observed during the manual transfer, as compared to prior research, may be attributed to patient assistance during the transfer procedure. Despite instructing patients to abstain from aiding the caregivers, the limited space and the additional requirement to avoid stepping on the force plate heightened the difficulty of the transfer, leading some patients to inadvertently aid the caregivers during the manual transfer.

These requirements of carrying out the transfer on the force plates could have also caused the nurses to adopt an atypical posture possibly affecting the spinal loads and muscle activations measured.

Despite the significant reduction in spinal loads and muscle activity achieved when using the lifter prototype, the much longer duration of the transfer process could also potentially result in WMSDs. The longer time taken for the transfer using assistive devices such as the lifter has previously been investigated. It was shown that most patient handling assistive equipment take substantially longer than manual transfers that lead to longer exposure and a larger cumulative load on the body. Methods used to measure and analyse cumulative lower back loads could be used to further quantify the effect of this risk factor and further optimise the transfer process. Additionally, the use of a thigh strap may cause discomfort for patients due to the thick seams causing high interface pressures at their thighs (Peterson et al. 2015). As such, it is imperative that interventions such as the ones tested in the study also focus to reduce the total transfer time and to minimise the duration in which patients are suspended mid-air.

There were also a few issues faced when using the Xsens motion capture system. The Xsens motion capture system was also found to produce less than accurate results when the subjects were squatting due to the pelvic sensor to sliding upwards (soft tissue artifacts). This resulted in the need for frequent recalibrations during the experiment and exclusions of trails during the AnyBody modelling simulation stage. Another possible cause of errors in the segment angles during recording is the proximity of the Xsens measurement system near the car (a large metal object). However, this problem known to the inertial motion capture systems appear to have been largely solved as no large deviations in segment angles were observed (compared to video footage) when the recommended calibration method (Npose + walk) was used.

Only two types of transfers are investigated in this study. More research on the various available devices in the market as well tests on different types of vehicles would help engineers achieve better designed solutions and buyers make more informed purchases.

Future Improvements and Suggestions

Modifications to the NEAR-1 prototype are presently underway. To enhance patient comfort during the transfer process, a redesigned sling with seams that do not produce high contact forces with the patient's thighs should be employed. Additionally, a faster and more secure attachment mechanism should be implemented to reduce the setup time required for patient transfer thus also reducing the time spent by caregivers stooping or squatting.

Car transfers are required for households and care homes catering to the elderly and the mobility impaired who frequent hospitals for regular medical appointments. Designing and developing interventions that work for regular indoor transfers (bed-to-wheelchair, wheelchair-to-commode, etc.) as well as car transfers could translate to cost saving for the end user. This could then make the device a lot more accessible and attractive to the emerging nations. The lifter prototype is seen as a first step in designing and developing such a device.

CONCLUSION

This study has quantitatively assessed the biomechanical loads experienced by caregivers during the patient transfer process into and out of a car. The muscle activations in the ES_{left} ($p < 0.001$), ES_{right} ($p = 0.0028$), AD_{left} ($p = 0.007$), and BB_{left} ($p = 0.003$) muscles are shown to be significantly lower when using the lifter prototype compared to the manual transfer. The axial compression ($p < 0.001$) and AP shear ($p < 0.001$) joint reaction forces at the L5/S1 disk also show a significant reduction using the lifter prototype when adjusted for equal patient weight. The use of the lifter prototype (a simple mechanised solution) is shown to reduce the muscle activations in certain muscles and reduce lumbar compression forces experienced by the caregivers to a safer level. Better patient transfer solutions that remove the need for lifting are required to further reduce the burden of car transfers on caregivers.

The findings of this study suggest that car transfers represent a significant concern that necessitates the attention of decision-makers. Repeated transfers pose a high risk of developing lower back WMSDs for the caregivers. Implementing and utilising transfer aids, such as the lifter prototype, could potentially serve as a solution to mitigate this issue. Ultimately, this course of action would promote enhanced safety measures and a decrease in the prevalence of WMSDs among caregivers.

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Conflict of interest: The NEAR-1 lifter prototype was designed and developed by researchers and students in the same laboratory as the one conducting this study. Despite this association, rigorous methodological controls (manual method) and analytical adjustments of confounding effects (patient weight) were implemented throughout the experimental protocol and data analysis to ensure objectivity and minimise potential bias in the evaluation of the lifter prototype's efficacy.

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