User Satisfaction and Functional Trunk Support Using a Robotic Assistive Device: A Pilot Study

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ABSTRACT

Background: Neurological, spinal, or age-related variables can cause trunk mobility impairments, which impair posture control and raise the risk of falls, both of which have an adverse effect on quality of life. Few active and passive trunk-assistive devices have been created to help these people, but their portability, range of motion, and customizability are limited. The aim of this study is to create and assess a novel, active trunk assistive technology that overcomes these constraints.

Methodology: An active wheelchair add-on device design was suggested using intelligent Dynamixel actuators. Its four degrees of freedom movement design comprised movable pulleys and a configurable jacket harness. Ten healthy participants (male: age 31.2 ± 6.55 years and female: age 26.5 ± 6.61 years) completed the Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) and System Usability Scale (SUS) questionnaires to provide feedback on the device's performance. Additionally, statistical analysis was used in order to further evaluate device usefulness.

Results: A high degree of user satisfaction is shown by the QUEST score of 4.2 ± 0.4 and the SUS mean score of 71.25 ± 7.84, with 7 participants exceeding the threshold of 65. P-value (0.041) < α (0.05) in one sample t-test on SUS scores indicated higher device usability than the acceptable score of 65. The outcomes confirm how well the design works in terms of convenience, comfort, and security.

Conclusion: The suggested design demonstrated the potential to enhance trunk mobility and support everyday activities for those with poor trunk control because of its increased range of motion, adjustable harness, and portability. It effectively addresses the shortcomings of the current trunk support devices.

Keywords: Assistive, Independence, Mobility, Neurological, Robotic, Trunk

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INTRODUCTION

Trunk is the central part of the human body, and its mobility disorders are characterized by restrictions in its ability to move and control [1] significantly affecting posture, stability, and overall quality of life. [2, 3] Trunk mobility limitations are associated with a wide range of neurological and neuromuscular disorders. These include multiple sclerosis[4], muscular dystrophy, [5] stroke,[3] amyotrophic lateral sclerosis (ALS), [6] cerebral palsy, [7] and spinal cord injuries, [8] all of which impair motor function, balance, and coordination. Additionally, reduced trunk function may also be exhibited by individuals with general neurological impairments affecting motor control and balance. Moreover, age-related degeneration is another major contributor to trunk mobility issues. Geriatric individuals often experience decreased flexibility, muscle strength, and postural control due to natural ageing processes, which further increases their risk of falls and functional decline. [9]

About 27 million persons (12. 7% of the population) in Pakistan suffer from some kind of disability, with physical impairment accounting for the majority. Wheelchairs are used by an estimated 131.8 million persons worldwide. Due to their impaired trunk mobility, these people struggle with everyday tasks including eating, bending, and walking, as well as limited range of motion and bad posture. [1] These difficulties frequently lead to a higher risk of falls, less independence, and a worse standard of living. Assistive trunk support devices, both passive and active, have been developed to address these problems with the aim of enhancing trunk control, improving posture, increasing safety and comfort during the activities of daily living.

Several active and passive devices have shown promise. For instance, a passive trunk support system designed for Duchenne Muscular Dystrophy (DMD) patients reduced lumbar muscle activity using five strategically placed pads connected by polycarbonate links allowing one degree of freedom. [10] Another device, the Chair-Mounted Passive Trunk Orthosis (CMPTO), featured spring-based actuators and provided 4 degree of freedom. [11] In contrast, active trunk support systems provide powered assistance. The Trunk Drive device, also developed for DMD patients, used electromechanical actuators controlled via various interfaces (EMG, joystick, force sensors), allowing limited 1 degree of freedom movement for evaluation purposes. [12] Similarly, the WRAPS system used a complex kinematic structure actuated by linear actuators to enable 4 degree of

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freedom with a rigid structure and direct actuator-body contact. [13]

Existing technologies have limitations despite their potential, such as limited range of motion, poor mobility, and lack of customisation. In order to address this, we have created a Robotic Trunk Assistive Device (RTAD) that provides enhanced trunk mobility in a lightweight, portable, and easy-to-use manner. Our concept, which was influenced by CMPTO, uses motorized pulleys in place of passive springs to provide four degrees of freedom. The active pulley mechanism enables smooth, regulated motion, and a customisable harness system guarantees user comfort and safety. This modular gadget supports people with trunk impairments during daily activities and is designed to be an add-on for wheelchairs and seating solutions. This system provides a promising step toward improving trunk mobility, comfort, and quality of life for users with neurological and age-related trunk diseases through meticulous mechanical design, modeling, and validation.

METHODOLOGY

Mechanical Design of the Device

The mechanical designing of the device first started with rough sketching and calculation of the dimensions and geometry of the parts of the mechanical structure including motor mount, two rotating and two motor pulleys along with the acrylic discs for their connection and overall structure of the proposed device. This was later 3D modelled shown in Figure 1(a) on Fusion 360 to visualize the design and make necessary adjustments before manufacturing. This process ensured that the hardware components were accurately produced according to our design specifications, contributing to the overall success of our project. The finalized design was implemented to manufacture a new mechanical framework on which the cables, motor and harness was later attached.

Overall, the mechanical design of the hardware shown in Figure 1(b). It weighs 4.1kg which was not directly in contact with the user. The weight of this portable device was borne by the wheelchair and did not restrict the independence of the user as in WRAPS. [13] The mechanical hardware consisted of the following parts:

1. *SS Framework:* The light weight Stainless Steel (SS) framework in Figure 1(b) consisted of a supporting base plate of size 19 x 5.5 inch^2 and thickness 1.59mm, two vertical shafts of size 1x1 inch^2 and height 15.8 inches, motor pulley mounts and two horizontal arms that helped to integrate it into various wheelchair systems. SS was strategically opted as the primary material for the body of this innovative orthosis. This material choice aimed to overcome weight concerns while ensuring strength and durability.
2. *Motor Mounts:* The motor mounts in Figure 1(a) secured the motors firmly on the base plate close to the shaft on either side such that both motors face each other.
3. *Motor Pulleys and Mount:* Motor pulleys in Figure 1 (a & b) were fixed with the pulley mount on the base plate that were driven along the motors for winding and unwinding of the cable.

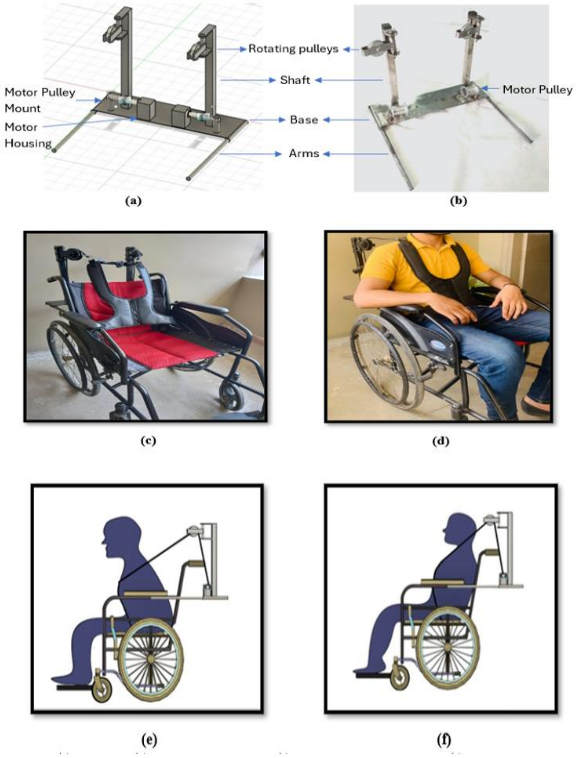


Figure 1. The RTAD. (a) CAD Model (b) SS Mechanical Structure (c) wheelchair mount and (d) with user. The schematic diagrams showing (e) forward (f) backward movement of user

4. *Motor Pulleys and Mount:* Motor pulleys in Figure 1 (a & b) were fixed with the pulley mount on the base plate that were driven along the motors for winding and unwinding of the cable.
5. *Motor Pulleys and Mount:* Motor pulleys in Figure 1 (a & b) were fixed with the pulley mount on the base plate that were driven along the motors for winding and unwinding of the cable.
6. *Connector Plates:* They worked as the interface between the rotor of the motors and motor pulleys allowing the synchronized motion of the motor and pulleys.
7. *Rotating Pulleys:* Rotating pulleys in Figure 1(a & b) made out of Aluminum were mounted on the two vertical shafts that allow 4 degree of freedom in frontal and sagittal plane.
8. *Harness:* A customizable and easy to wear jacket harness with zipper closure in Figure 1 (c & d) supported the trunk and prevented falls that could be connected to the wheelchair via locking straps and attached to the framework with cable.
9. *Cable:* Two separate cables shown in schematic diagram in Figure 1(e & f) were attached to the shoulder straps of the harness at one end while the other end passes over the rotating pulleys and fix at the motor pulleys to wind around them. Strong clutch cables were used in our design to ensure strength and resistance to deformation. The length (S) of the cable wrapped per rotation of the motor pulley of radius (r) was calculated using equation 1 and was calculated to be 2m.

$$\boldsymbol{S = 2\pi r}$$

Table 1. Comparison of device degree of freedom and weights between our device (RTAD) and existing trunk orthotic systems.

Device Name	Type	Degrees of Freedom	Total Weight (kg)
RTAD	Active, Soft-Mount	4	4.1
CMPTO [11]	Passive, Chair-Mounted	3	7.3
WRAPS [13]	Active, Rigid Frame	4	8.5
Trunk Drive [10]	Active, Fixed Base	1	5.5 – 6.0

Actuation Mechanism

We have selected Dynamixel MX-106T/R motors (Robotis, USA) as the device actuators due to reliable actuation technology, higher degree of precision and smooth position control over 360 degrees as required in our device. Its angular velocity of 42 rad/sec, maximum torque 8 Nm and resolution of 0.088 degrees smoothly allows the controlled movement of the device. The motors were firmly mounted within the motor mount of the mechanical framework and linked to motor pulleys via connector plates, enabling synchronous rotation with the motors. The motor pulleys lock one end of the cable while the other end was connected to the harness. This allows the winding and unwinding of the cable around the motor pulleys as the motors, enabling both to and fro (shown in Figure 1 (e & f)). as well as left and right movement of the user. The actuation is powered by a 12 Volts adapter directly connected to the AC power source.

Control Strategy

The control of the motors is achieved through programming on MATLAB by using Dynamixel Software Development Kit (SDK) along with U2D2 PID controller and SMPS2Dynamixel for distributing power (12V 5A SMPS). The U2D2 PID controller allowed communication between Dynamixel and computer at two different signal levels i.e. TTL for Dynamixel MX106T with 3 pins connector and RS482 for Dynamixel MX106R with 4 pins connector.

Evaluation of the Design

We have performed the evaluation of the design by testing the ability of the device to smoothly allow forward bending and return to original position. This was done by giving computer commands to the motors to follow specified goal position using Dynamixel Wizard software to configure and test Dynamixel motors. The software also tracked the present and goal position of the motors. The variation between present and goal position of the motors is assessed to determine the validation of the design that allows proper functioning of the device.

Participants Recruitment and Training for Performance Evaluation

A total of 10 participants were recruited to test the usability of the device from the university and local community (demographics shown in Table 2). The inclusion criteria were healthy adult volunteers with no known history of neurological, musculoskeletal, or systemic disease. The participants included both males (mean ± SD; age: 31.2 ± 6.55 years, BMI: 24 ± 4.53 kg/m^2, height 166.8 ± 3.05 cm) and females (mean ± SD; age: 21.8 ± 0.4 years, BMI: 19.4 ± 3.11 kg/m^2, height 164.2 ± 1.94 cm) which allowed for a broader assessment of device performance and usability across distinct demographic groups.

All participants received comprehensive training by the authors on the usage of the RTAD prior to the start of the performance evaluation led by the development. The participants were instructed to remain relaxed throughout the session and let the harness fully support and regulate their trunk movement.

A random forward goal position was given for each participant during the test using Dynamixel wizard. Their trunk was then actively guided forward by the device, allowing for a controlled flexion. The user was returned back to their initial upright posture by the device after holding this position for a few seconds. To evaluate the comfort, responsiveness, and efficacy of mobility aid, this cycle was repeated a few times.

All procedures involving human subjects were executed in compliance with the ethical criteria set out by the Research Ethics Committee of NED University of Engineering and Technology (approval no. ASRB/878) and followed the tenets of the Declaration of Helsinki, together with its subsequent revisions. Participation was optional, and informed consent was acquired from all individuals before their engagement in the study. The participants' data was ensured to be kept confidential throughout.

Table 2. Participants' demographics

Participants	Gender	Age	Weight (kg)	Height (cm)	BMI (kg/ cm²)
1	Male	33	82	170	28.4
2	Male	38	76	167	27.3
3	Female	22	57	162	21.7
4	Female	22	52	162	19.8
5	Female	22	57	165	20.9
6	Female	22	58	165	21.3
7	Male	23	50	170	17.3
8	Male	24	52	162	19.8
9	Female	21	37	167	13.3
10	Male	38	74	165	27.2

User Feedback

The System Usability Scale (SUS) and Quebec User Evaluation of Satisfaction with Assistive Technology (QUEST) standard questionnaires are used to collect input on the device's functioning and user experience.

The subjective perception of usability is evaluated using the SUS. Each of the ten items is assessed on a 5-point Likert scale, with 1 denoting "strongly disagree" and 5 denoting "strongly agree." Positive and negative stetements alternate throughout the items, with odd-numbered items representing positive aspects and even-numbered things representing negative ones. Each component is first translated to a standardized value in order to determine the final SUS score. One is deducted from the user's response for positively written (odd-numbered) items. The user's answer is deducted from 5 for negatively phrased (even numbered) items. Individual item scores range from 0 to 4 as a result. The ultimate score, which ranges from 0 to 100, is obtained by adding the scores from all ten items and multiplying the result by 2.5. Better perceived usability is indicated by a higher SUS score; a score above 68 is typically regarded as above average.

The QUEST is designed to objectively measure usability and gauge user satisfaction. The twelve items are split into two categories: satisfaction with the equipment and happiness with the service that goes along with it. A 5-point Likert scale is used to score each item on the QUEST, with 1 denoting "not satisfied at all" and 5 denoting "very satisfied." Both the assistive device and the services associated with its provision, such as delivery, follow-up, and repairs, are rated by users. An overall satisfaction score is calculated by analyzing the scores for each segment. Increased user satisfaction with the product and related services is reflected in higher scores.

Both the standard questionnaires are scientifically proven. The reliability of SUS is shown through its high internal consistency with a Cronbach's alpha of 0.91 over 2,324 usability tests. [14, 15] The QUEST also demonstrated strong dependability with a Cronbach's alpha of 0.87 [16] for its device component, indicating that it is appropriate for evaluating assistive technology.

Statistical Analysis

A one-sample two-tailed t-test in SPSS software was employed to perform statistical analysis on data collected using the SUS questionnaire. The scores from 10 participants were compared with an acceptable score of 65 (out of a possible 100) to assess whether the mean SUS score of these participants significantly deviates from the ideal score. The two-tailed test allows for the possibility of observing differences in either direction (either higher or lower than 65). The significance level was chosen to be 0.05. The QUEST consists of 12 items assessing user satisfaction with both the assistive device and the services provided. To analyze the results, descriptive statistics were employed. Specifically, the mean score for each item was calculated by averaging the responses from all participants, providing a measure of overall satisfaction for each aspect. In addition, the standard deviation was computed to capture the variability of responses, indicating the degree of agreement or divergence among participants. This was done to identify which aspects of the device and services were consistently rated high or low, and which items exhibited the most variability in user perception.

RESULTS

I) Validation of the Design

The effectiveness of the device design is evaluated by examining whether the actual positions of the motors align with the intended target positions. In the graph presented in Figure 2, the positions (y-axis) are plotted against time (x-axis), with the red line indicating the target position and the yellow line representing the present position of the motors. The graph shows that the present positions closely follow the target positions. This suggests that the device design functions accurately and does not hinder the overall efficiency.

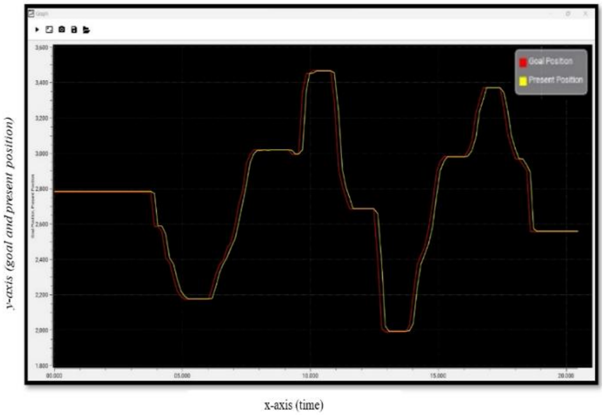


Figure 2. Graph of MX-106 Dynamixel motor showing Goal and Target positions against Time

II) User Feedback

The user feedback collected through SUS and QUEST questionnaires shows the device usability and user experience.

User Experience:

Figure 3 shows the number of users who reported the different levels of satisfaction against each of the 12 items of the QUEST questionnaire. The scores for each item Dimensions, Weight, Adjustments, Safety, Durability, Easy to use, Comfort, Effectiveness, Service Delivery, Repairing/Servicing, Professional Service, and Follow-up Services were (mean ± SD): 4.3 ± 1.06, 4.3 ± 1.49, 4.6 ± 0.70, 4.8 ± 0.42, 4.5 ± 0.85, 4.5 ± 0.71, 4.7 ± 0.48, 4.4 ± 0.84, 4.1 ± 1.20, 4.5 ± 0.71, 4.9 ± 0.32, and 4.4 ± 0.84, respectively. The highest score was for Professional Service, where 9 out of 10 users were very satisfied. The lowest score was for Service Delivery, where 6 out of 10 users were very satisfied. Moreover, the average scores for device satisfaction (items 1-8) were 4.51 ± 0.77 whereas those for service satisfaction (items 9-12) were 4.48 ± 0.71.

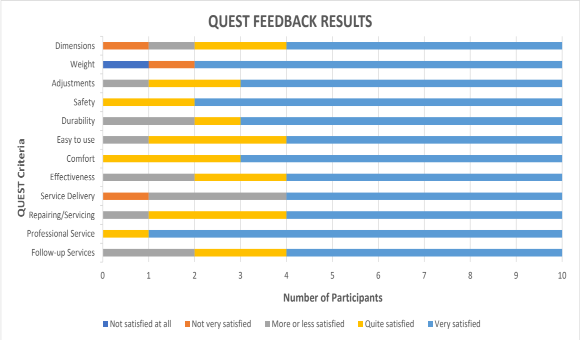


Figure 3. The user responses for QUEST questionnaire

Device Usability:

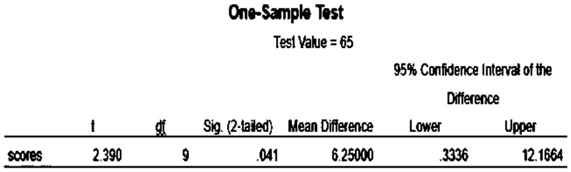
Table 3 shows the user responses for the SUS questionnaire. Each row represents an item of the questionnaire. The average user responses are given as mean ± standard deviation. The ideal scores for each item are given as 5 (for positive aspect) and 1 (for negative aspect). The deviation of the mean score from the ideal score is given in the last column, representing the true magnitude of the score. The highest score deviation from ideal was for the question ‘I think that I would use the device frequently’, whereas the lowest one was for ‘I felt very confident using the device’. Overall, we found a mean SUS score of 71.25 ± 8.27 out of 100. Seven participants reported a score higher than the set threshold of 65. The division of participants into male and female showed an average SUS score of 72 ± 10.2 and 70.5 ± 4.2 respectively.

Table 3. The user responses for SUS questionnaire

	System Usability Scale Questions	Mean ± SD(S)	Ideal Score (E)	Deviation (E-S)
1	I think that I would use the device frequently.	2.2 ± 0.6	5	2.80
2	I found the device unnecessarily complex.	2.9 ±1.166	1	1.90
3	I thought the device was easy to use.	4.4 ± 1.04	5	0.60
4	I think that I would need the support of a technical person to be able to use the device.	2.5 ± 1.1	1	1.50
5	I found the various functions in the device were well integrated.	4.3 ± 0.748	5	0.70
6	I thought there was too much inconsistency in the device.	1.8 ± 0.871	1	0.80
7	I would imagine that most people would learn to use the device very quickly.	4.3 ± 1.135	5	0.70
8	I found the device very cumbersome (awkward) to use.	1.5 ± 0.663	1	0.50
9	I felt very confident using the device.	4.6 ± 0.670	5	0.40
10	I needed to learn a lot of things before I could get going with the device.	2.6 ± 1.268	1	1.60

The results show that most users strongly agree that the device is easy to use, without the need of any technical help and prerequisite training, indicating active utilization. Additionally, most users were found confident using the device. The larger deviation in the mean score for Question 1 can be attributed to the fact that the device was tested by healthy subjects, who did not feel the need to use it frequently.

Figure 4 shows the results from the one-sample t-test statistics. We found the score to be significantly higher than the acceptable score of 65 (t = 2.390, df = 9, significance = 0.041). The statistically significant mean positive difference of 6.25 between the observed mean SUS score of 71.25 and the acceptable value 65, suggested that the device has greater usability than the acceptable value.



One-Sample Test

Test Value = 65

	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference Lower	 Upper
scores	2.390	9	.041	6.25000	.3336	12.1664

Figure 4 Statistical analysis of the SUS scores**.**

DISCUSSION

This study provides an enhanced and user-centric design for an active trunk support system in order to increase comfort, portability, and functional support for people with trunk mobility disabilities. Participants' positive feedback highlight the usefulness of the suggested design elements, which were purposefully incorporated to overcome shortcomings in the current trunk support systems.

The developed design's major emphasis on weight reduction, which acknowledges portability as a crucial component of user ease, are its main innovations. As shown in Table 1, comparative evaluations with current devices [11, 13] show a significant weight decrease. The suggested method, in contrast to many existing devices, can be easily incorporated into wheelchair setups, guaranteeing accessibility and adaptability for a wider range of users.

The personalized chest harness was designed to accommodate users' various anatomical and functional requirements, providing a pleasant and customizable fit. This is in contrast to conventional devices, which frequently have set designs and stiff orthotic structures. [10, 13] additionally, four degrees of freedom are made possible by the use of motor and spinning pulleys, which improves range of motion in comparison to traditional active orthoses. [12] By reducing the number of actuators to two and placing them away from the body, our design improves both comfort and safety in contrast to previous systems that have numerous heavy actuators [13] in direct touch with the body.

The software and hardware interface were utilized by the control architecture. These can be included with a microcontroller to simplify the hardware configuration after being tested with a computer. Using lightweight, large-capacity batteries to power the system could help improve its autonomy and operating time. [17] Future research may examine the use of carbon fiber or advanced composites to further reduce weight without sacrificing durability, even if the pulleys and frame were made of aluminum and stainless steel to preserve structural strength. [18]

The majority of users reported acceptable usability levels [19] when usability was evaluated using validated techniques. Items pertaining to device functionality and usability received high marks, suggesting that consumers thought the system was simple to use and efficient. One item, however, scored comparatively lower, probably because the device was designed for people with trunk deficits but was tested on healthy participants. This implies that the clinical population may not be immediately affected by some usability issues. Concerns about how users with impairments might receive support could be the reason for another comparatively poor score of service delivery. Notably, this issue was unrelated to the device's primary functionality and may be resolved with the right instruction, user guides, and support services.

Future research shall concentrate on automating motor control by predicting user intent [20] using machine learning models trained on EMG and IMU inputs. Patient trials shall be carried out to assess the device's performance in practical situations following extensive internal validation. Additional suggestions include obtaining input for design improvements, investigating economical production techniques, and tracking long-term impact and durability through user-centered research. Moreover, EEG sensors may be integrated to assess user engagement. [21, 22]

Limitations

Despite the encouraging results, there exists potential limitations. Firstly, the usability findings of the current study cannot be applied directly to the real clinical population. However their input is essential in determining the design usability and ergonomic advantages and disadvantages. There is still a need to evaluate the RTAD performance and acceptability in patients with the trunk mobility issues. Secondly, the RTAD reduces the weight while comparing to the current existing solutions, [11, 13] persons with the weak upper body may still finds the weight difficult. This burden might be lessened by further structural component optimization, such as the use of lightweight composites or 3D-printed frames. Lastly, the absence of safety features like stop switches and fail-safes that was needed in the current study due to the healthy population but, is crucial for its practical implication in the real clinical scenarios.

CONCLUSION

In conclusion, the proposed design of an active trunk assistive device aims to enhance the trunk mobility and balance in patients with poor trunk control due to disease, injury, or ageing, to improve their quality of life and allows them to perform their daily tasks independently like a healthy person. Positive user feedback and design validation affirm the effectiveness of the Robotic Trunk Assistive Device in meeting its intended purpose. This innovative design has successfully addressed the limitations of customization, limited range of motion and portability issues found in the existing trunk assistive devices, with its customizable jacket harness, rotating pulleys and add on device feature.

Conflict of Interest:

The authors declare that there is no conflict of interest.

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Author's Contribution

AZR, MAH, GAKG, and MZS contributed to the conception and design of the study. Data collection, analysis, and interpretation was performed by MZS, BM, and RA. Manuscript drafting and critical revision were undertaken by all authors. All authors have read and approved the final manuscript.

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