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DEVELOPMENT AND EVALUATION OF PASSIVE EXOSKELETON (SOLATEXO) FOR ASSISTING MUSLIMS WITH PHYSICAL DISABILITY IN SALAH

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ABSTRACT: Performing Salah (Islamic prayer) is a fundamental practice for all Muslims worldwide, involving physical movements such as standing, bowing, and prostrating. However, these movements can be challenging for individuals with physical disabilities, who often rely on conventional chairs to support their bodies during Salah. Using conventional chairs presents limitations in mosques, disrupting congregation alignment and hindering mobility due to their bulky size and lack of portability. To address these challenges, this study aimed to design and develop SolatExo, a passive exoskeleton prototype tailored to assist Muslims with physical disabilities during Salah. The study evaluated SolatExo's impact on range of motion (ROM), muscle contraction using electromyography (EMG), usability, and user experience. Key findings indicated no significant reduction in ROM between wearing and not wearing SolatExo. The EMG analysis revealed reduced muscle contraction with SolatExo, suggesting its potential to alleviate muscular effort during Salah. Usability assessments yielded a moderate to good System Usability Scale (SUS) score of 68, although user feedback highlighted operational difficulties, particularly during transitions between Salah postures. This study underscores the importance of interdisciplinary collaboration between biomechanics, assistive technology design, and religious studies to develop inclusive solutions for enhancing Salah accessibility. Future research should focus on refining SolatExo's design to improve usability and user experience, addressing comfort issues and incorporating advanced ergonomics principles better to serve the diverse needs within the Muslim community.

ABSTRAK: Mendirikan solat merupakan amalan wajib bagi semua umat Islam di seluruh dunia. Solat melibatkan pergerakan fizikal seperti berdiri, rukuk, dan sujud. Pergerakan ini sukar dilakukan oleh Muslim yang mempunyai kecederaan fizikal. Mereka akan menggunakan kerusi konvensional untuk solat. Walau bagaimanapun, kerusi konvensional akan mencetus beberapa kelemahan ketika solat di dalam masjid, seperti menjejaskan lurusnya saf jemaah, menghalang mobiliti dan mengganggu ruang jemaah lain kerana saiznya yang agak besar. Untuk menangani kelemahan ini, kajian ini bertujuan mereka bentuk dan membangunkan SolatExo, sebuah eksoskeleton pasif yang dicipta untuk membantu individu Muslim yang mempunyai kecederaan fizikal mendirikan solat. Kajian ini telah menilai kesan SolatExo terhadap julat pergerakan, penguncupan otot menggunakan elektromiografi, kebolehgunaan, dan pengalaman pengguna. Penemuan utama menunjukkan tiada perbezaan ketara dalam julat pergerakan di antara memakai dan tidak memakai SolatExo. Analisis elektromiografi menunjukkan pengurangan penguncupan otot ketika menggunakan SolatExo, bermakna ianya berpotensi mengurangkan usaha otot semasa solat. Penilaian kebolehgunaan menghasilkan skor Skala Kebolehgunaan Sistem yang sederhana tinggi iaitu 68. Dari aspek maklum balas pengguna, SolatExo memerlukan penambahbaikan terutamanya peralihan pergerakan solat yang lancar. Kajian ini menekankan kepentingan kerjasama pelbagai disiplin seperti biomekanik, reka bentuk teknologi bantuan, dan fiqh untuk membangunkan SolatExo yang berimpak tinggi. Penyelidikan masa depan perlu memberi tumpuan kepada memperhalusi reka bentuk SolatExo untuk meningkatkan kebolehgunaan dan pengalaman pengguna, aspek keselesaan dan menggabungkan prinsip ergonomik supaya memenuhi keperluan komuniti Muslim.

KEYWORDS: *Human Factors Engineering, Exoskeleton Design, Muslim Prayer, User Testing*

1. INTRODUCTION

The Islamic prayer (also known as Salah, Solat, or Salat) holds a significant place in Islam as the performance of prayers. Exoskeletons, defined as mechanical devices designed to augment body motion, find applications in fields such as military, rehabilitation, industrial tasks, and sports, categorized into passive, active, and soft exoskeletons [1]. For instance, active exoskeletons have been developed for soldiers to reduce fatigue and increase endurance in carrying loads [2]. In rehabilitation, lower-limb exoskeletons aid patients with spinal cord injuries in regaining the ability to walk [3]. Passive exoskeletons are often used in industrial tasks to reduce musculoskeletal strain during repetitive activities [4], while soft exoskeletons are being explored in sports to improve athletic performance [5].

In the context of Salah, exoskeletons can play a crucial role in supporting the body weight of individuals, aiding in maintaining the postures required for the compulsory movement of Salah, and facilitating smooth transitions between these movements. The potential users include individuals falling into categories such as elderly individuals with limited physical strength, those with lower limb disabilities (e.g., injured legs, arthritis), and individuals who face challenges standing for extended periods, as pointed out by a past study [6]. The development of exoskeletons tailored for Salah aligns with the goal of inclusivity, enabling individuals with physical limitations to engage more actively in their religious practices.

Developing an exoskeleton to assist Muslims with physical disabilities in performing their Salah is a commendable and potentially impactful initiative. Such a device could enhance accessibility and inclusivity, allowing individuals with physical challenges to participate more fully in prayer practices. The exoskeleton could promote inclusivity by providing individuals with physical disabilities the means to actively engage in Salah actively, fostering a sense of belonging within the Muslim community. Enabling individuals with physical disabilities to perform their Salah without difficulty can contribute to their ability to fulfill prayer obligations, enhancing their spiritual well-being. The development of technology that supports individuals with disabilities can empower them to lead more independent and fulfilling lives, both within and beyond religious practices. This research may receive positive support from the Muslim community and beyond, as it aligns with values of compassion, empathy, and the promotion of equal opportunities.

The problem statement concerns the limitations of using conventional chairs or foldable stools during Salah, particularly in congregational prayers. These issues include challenges in straightening the row or *saf* when using chairs, difficulty in achieving a close row due to the

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bulkiness of prayer chairs, the troublesome process of bringing in and positioning conventional seating in crowded rows, and the potential for disrupting other Muslims, especially those in the rear rows. Addressing these challenges by developing exoskeletons tailored for Salah can significantly improve the experience for individuals with physical limitations, promoting inclusivity and facilitating a smoother congregational prayer environment.

The existing literature reveals a notable research gap concerning the application of exoskeletons in Muslim practices such as Salah and Hajj. Most research has focused on enhancing performance or rehabilitation in irreligious contexts, leaving a significant area unexplored - how exoskeletons can assist in performing religious practices such as Salah. This manuscript addresses this gap by developing the SolatExo, a passive exoskeleton designed to help Muslims with physical disabilities perform Salah. The design of SolatExo considers Salah's unique postural requirements, providing support and stability during transitions between standing, bowing, and prostration. Given the limited research in this area, this study contributes to the growing body of knowledge on applying exoskeleton technology in a religious context, offering a novel approach to improving the quality of life for Muslims with physical challenges.

1.1. The Needs of an Exoskeleton for Salah

The need for an exoskeleton for Salah arises from the challenges faced by Muslims with physical injuries, such as knee pain, who encounter difficulties in performing Salah like able-bodied individuals, particularly in standing up from a sitting position. While conventional chairs are often relied upon for support, they present various drawbacks. Firstly, their usage disrupts the alignment of worshippers in the row behind during congregation, impeding the harmonious flow of prayer (Fig. 1). Secondly, conventional chairs lack portability. They are cumbersome to carry, hindering ease of movement for users. Additionally, bringing in and passing through chairs amidst a congregation poses logistical challenges and disruptions. The design and development of an exoskeleton for Salah (called SolatExo, developed by this study) address these shortcomings by offering lightweight, discreet, and ergonomically designed support that facilitates seamless integration into the Salah environment while ensuring the dignity and inclusivity of all Muslims, regardless of physical abilities.

As depicted in Table 1, Muslim Salah chairs and foldable Salah chairs are commonly utilized by Muslims during Salah, particularly if they have physical disabilities. In addition to these chairs, plastic, and banquet chairs are frequently employed. Previous researchers [6], [7] have introduced new designs for chairs intended for Salah. However, these designs have yet to address alignment in the rows and issues of bulkiness adequately. Furthermore, Table 1 explains the uniqueness of SolatExo compared to the chairs mentioned above.

Figure 1. Muslims with physical disabilities such as knee pain use conventional chairs or stool to support their body during Salah.

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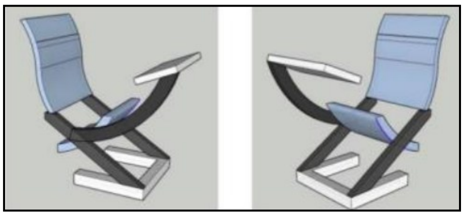
Table 1. Uniqueness of the SolatExo - a comparison with existing chairs

Chair for Salah and exoskeleton	**Design features**
 Muslim Salah Chair Sajda Chair Namaz Salah [8]	This chair facilitates people who do not have the ability to Salah. It has certain features, such as an armrest for placing both palms to suck in a sitting position, as well as a specially designed cushion to give comfort to the individual's back. The individual can also use the chair's armrests to counterbalance the downward lift-up force. Users will feel more at ease and comfortable in this situation because getting up from a sitting position is easier and more balanced.
 Foldable Salah Chair [9]	This folding chair is a commercial one and is most commonly used in musolla and mosque. It is light, simple in design, easy to carry, and easily available in the market. These features make this product a priority for everyone who cannot stand when praying. This chair can support a weight of up to 130 kg.
 [6]	This chair has features such as being lightweight, having a height regulator, being easy to fold, and being ergonomic for sitting. The height regulator adjusts according to the individual's height suitability.
 [7]	This chair has electronic components to help Muslims pray when they cannot stand. It has various features, such as a flexible design, a tool to help count the rakat during Salah, a sensor for the safety of the user's distance, and a tool to help recite and chant [7]. The main feature of this prototype is that the prostration panel and the seat are flexible to determine the degree to which the bowing and the act of prostration differ.

SolatExo (developed by this study)

A Muslim wearing SolatExo for walking and Salah

The SolatExo is an innovative exoskeleton designed to empower Muslim individuals with physical disabilities to perform Salah. Engineered as a wearable assistive technology, SolatExo seamlessly integrates with the wearer's trousers, boasting a lightweight and slim design for optimal comfort and discretion. Its advanced kinematic compatibility ensures natural movement, allowing users to effortlessly stand from a sitting position with the assistance of mechanical ratchets. One of SolatExo's key features is its ability to enable users to align their body positions with fellow worshippers in the row, fostering a sense of unity and inclusivity in congregational prayers. Moreover, its portable nature ensures minimal disruption to neighboring worshippers, making it an invaluable tool for individuals seeking to participate in their spiritual practices fully.

1.2. Research Questions and Objectives

In this study, the authors investigated the following research questions: (1) What essential features are needed by users for SolatExo? (2) To what extent does SolatExo reduce the range of motion of users during Salah? (3) How does SolatExo impact muscle contraction patterns in users while performing Salah? (4) What are users' perceptions of the usability of SolatExo in the context of aiding them during Salah? (5) What specific feedback do users provide after utilizing SolatExo in their Salah?

This study aims to design and develop a functional prototype of a passive exoskeleton named SolatExo, intended to assist Muslims with physical disabilities in performing Salah. Additionally, this study evaluated the effects of the SolatExo prototype on muscle contraction, ROM, and usability. The practical implications of SolatExo, explicitly designed for Salah, are profound and multifaceted. One of its primary objectives is to enhance Salah's perfection, emphasizing the congregation's alignment in a well-positioned and straight row, a fundamental requirement for congregational prayers. By supporting body motions and postures, SolatExo

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not only aids users in performing Salah but also addresses challenges associated with conventional seating methods. Furthermore, the use of SolatExo aims to create a harmonious prayer environment. Unlike conventional chairs or foldable stools that may disrupt the alignment of the congregation or pose challenges in maintaining close distances between worshippers, SolatExo seamlessly integrates into the Salah experience. The technology ensures that users with exoskeletons do not interfere with others during Salah, fostering an atmosphere of tranquility and focus during congregational prayers. In this way, SolatExo goes beyond individual assistance; it actively contributes to the collective experience of worshippers, promoting a more inclusive and harmonized congregational prayer setting.

2. MATERIALS AND METHODS

The development of the SolatExo involved a systematic approach, incorporating both user-centered design principles and technical evaluations to ensure that the exoskeleton met the needs of individuals with physical disabilities performing Salah. This section outlines the key processes undertaken, starting with a survey of user requirements to identify functional needs (Section 2.1). The gathered insights were then translated into technical specifications during the design conceptualization phase (Section 2.2), followed by the creation of detailed three-dimensional computer models for precision and refinement (Section 2.3). The fabrication process (Section 2.4) brought the digital design into a physical prototype, which was subsequently tested through range of motion (ROM) assessments (Section 2.5) and muscle contraction analysis (Section 2.6) to evaluate its performance. Then, a usability study (Section 2.7) was conducted to evaluate the ease of use of the SolatExo. Finally, user experience testing (Section 2.8) assessed the overall effectiveness and user experience during Salah movements.

2.1. Survey of User's Requirements

The survey aimed to identify the design features of the SolatExo that potential users would need. A questionnaire was developed using Google Forms and distributed to various Muslims across Malaysia. Participants were selected through a purposive sampling, aiming to include individuals who could represent a broad range of perspectives based on their physical abilities, age, and gender. Inclusion criteria required respondents to be Muslim, aged 17 years old and above, and able to perform Salah independently or with assistance. No prior experience with exoskeletons was required. Exclusion criteria included individuals with severe cognitive impairments that could hinder their ability to complete the survey.

The questionnaire was written in both English and Bahasa Malaysia to ensure all respondents could fully comprehend the questions. The cover page outlined the survey's purpose, explained the SolatExo, and included pictures of the exoskeleton. The survey gathered demographic information, such as age and gender, and specific user insights. Respondents were asked about their willingness to use the SolatExo if needed, their acceptance of using it for Salah, and their intent to purchase the SolatExo. Additionally, factors influencing their decision to purchase the SolatExo, such as price, aesthetic value, functionality, usability, and durability, were rated on a Likert scale, ranging from "Strongly disagree" (score = 1) to "Strongly agree" (score = 5). The questionnaire also provided an open-ended section for respondents to suggest other design features based on their needs and preferences. This approach allowed for a comprehensive understanding of the potential users' requirements while ensuring a diverse sample, thus aiding in developing a user-centered design for SolatExo.

2.2. Design Conceptualization

Once the user's requirements were gathered, these needs were translated into detailed technical specifications. The design conceptualization of the SolatExo began with translating the specific needs of users, primarily individuals with physical disabilities who face challenges in performing Salah. The primary objectives were to ensure that the SolatExo provided sufficient support during the main postures (e.g., standing, bowing, and prostration) while maintaining user comfort, ease of use, and alignment with the Salah perfection. Key performance criteria were established, including support for the knee, control of movement during sit-stand and standing-to-prostration transitions, and ensuring that the SolatExo would be lightweight and easy to wear. Anthropometric data from the target users were incorporated to ensure that the SolatExo would accommodate the 5th, 50th, and 95th percentile of the Malaysian population, especially focusing on lower limb dimensions for proper joint alignment and support.

Following this, initial design sketches were created to explore potential solutions. Various concepts were drafted, each offering different mechanisms of support and flexibility. These sketches focused on placing critical components, such as upper and lower structures, ratchets for controlled movement, and attachment systems for securing the SolatExo to the body. The sketches were also aimed at optimizing the ease of donning and doffing the exoskeleton to ensure that users could wear it with minimal assistance.

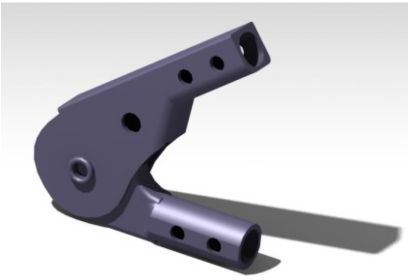
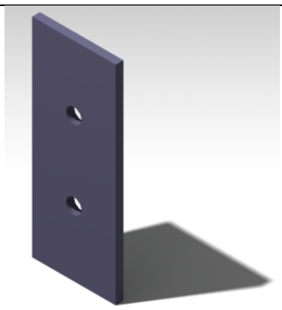
The design screening process then involved evaluating these sketches against the technical requirements and user needs. Multiple iteration cycles were carried out, wherein each concept was analyzed for its feasibility, practicality, and alignment with the Salah movements. This stage included reviewing the materials and mechanisms that could best serve the intended functions of the SolatExo, such as selecting lightweight materials like aluminum sheets for structural components and ensuring the durability of mechanical joints. Design alternatives were discussed, and those that showed potential for improving user experience, stability, and manufacturability were shortlisted for further development.

2.3. Three-Dimensional Computer Modeling

The outcome of the design conceptualization phase provided a clear foundation for the next step - the drafting of three-dimensional computer models. The finalized design concept transformed the sketches into detailed 3D representations using CAD software. This allowed for precise modeling of the SolatExo's components, enabling further refinement of dimensions, joint placements, and overall fit before moving on to the fabrication phase. Table 2 lists the components of the SolatExo that support the user's lower body. The upper and lower structures support the thighs and calves, respectively. The ratchet, hinge, and joint sheets assist with movement and stability at the knees and ankles. A foldable hinge is used for adaptability, bases offer foundational support, and isolated bolts and nuts ensure structural integrity.

https://doi.org/10.31436/iiumej.v26i1.3430

Table 2. List of components/ parts of SolatExo

No.	Components / Parts	Quantity	Material Description
1	 Upper structure	2	The upper structure of the SolatExo is aluminum sheet (270 mm x 30 mm x 3 mm), provides support to the user. It was attached to both thighs to provide stability in the knee-to-hip area.
2	 Lower structure	2	The lower structure of the SolatExo is aluminum sheet (380 mm x 30 mm x 3 mm), provides support to lower limb. It was attached to calves to provide stability in the knee-to-foot area.
3	 Ratchet	2	This steel ratchet connects the upper structure and the lower structure. It facilitates controlled movement and stability during sit-to-stand transitions. This ratchet was attached close to the knees to replicate this joint. This is a reverse circular ratchet used to restrict movement in one direction. The toothed components engage with the circular track, preventing undesired rotation. This mechanism ensures stability in specific postures, enhancing safety and control during activities where reverse movement needs to be limited, such as sitting down from a standing position.
4	 Joint sheet	2	The aluminum joint sheet (80 mm x 32 mm x 3 mm) supports the right ankle joint while maintaining flexibility.

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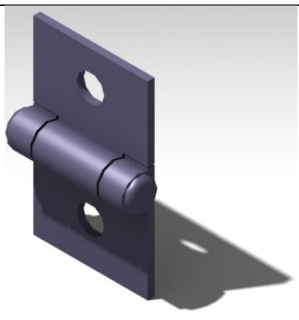
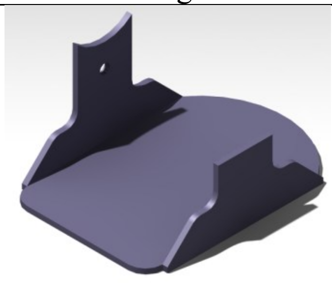
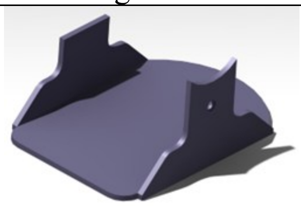
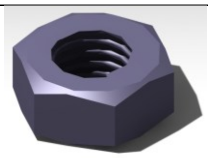
5	 Hinge	2	Enables folding of the ankles, accommodating various movements.
6	 Right base	1	The right foot's base is an aluminum sheet (102 mm x 80 mm x 3 mm) connected to the hinge, joint sheet, and bottom frame. This component assists with body stability.
7		1	The left foot's foundation is an aluminum sheet (102 mm x 80 mm x 3 mm) that mirrors the function of the right base.
8	 M6 bolt	12	M6 bolts are used to fasten and secure components of the exoskeleton.
9	 M6 nut	12	M6 nut secures the bolt in place, ensuring the stability of the connected components.

The SolatExo was designed using Fusion 360, and ANSYS software was employed for mechanical stress analysis. Stress analysis helps identify regions of high stress or potential failure in the SolatExo components. It is useful for determining the suitability of materials, verifying design parameters, and ensuring that the SolatExo is both safe and reliable. Stress analysis significantly aids in optimizing the structural design and reducing the risk of mechanical failures. Fig. 2 shows the 3D CAD model of the SolatExo and the results of the mechanical stress analysis.

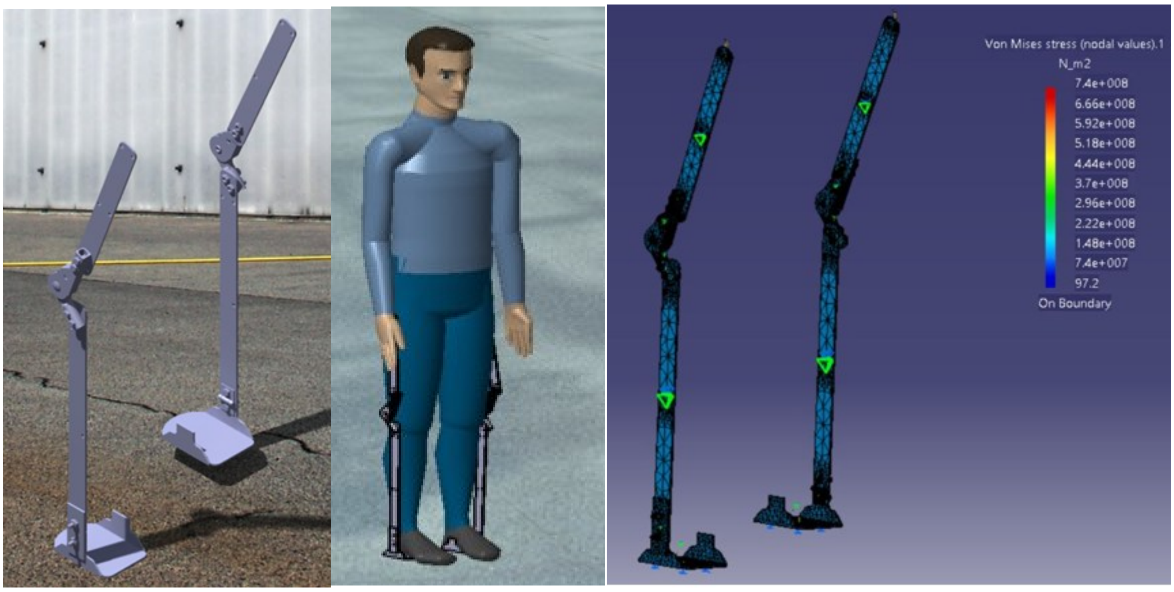


Figure 2. 3D CAD model of SolatExo and mechanical stress analysis

The overall height of the exoskeleton is 760 mm, the overall width is 50 mm, and the thickness is 3 mm. The weight of the exoskeleton is 2.55 kg. The SolatExo is designed to match the anthropometry of users at the 5th, 50th, and 95th percentile of the Malaysian population. A central focus of SolatExo design is its adaptability to accommodate anthropometry requirements, considering users at the 5th percentile for short users, the 50th percentile for medium-tall users, and the 95th percentile for tall users. The incorporation of six holes for height adjustability - three at the upper and three at the lower structures. Specifically, the hierarchical arrangement of these holes - level 1 for the 5th percentile, level 2 for the 50th percentile, and level 3 for the 95th percentile. This is to ensure optimal ergonomic support for users with diverse body dimensions.

The ratchet operating angle, or inclination angle, is also specified at 90, 72, 54, 36, and 18 degrees. These values likely indicate the range of angles or positions the exoskeleton can achieve, offering flexibility in supporting various movements or postures for users. The SolatExo was designed with adjustability to accommodate the 5th, 50th, and 95th of user anthropometrics. Table 3 presents the technical specifications of the SolatExo.

Table 3. Technical specifications of SolatExo

Item	Specification
SolatExo dimensions	
Overall height	760 mm
Overall width	50 mm
Thickness	3 mm
Weight (kg)	
SolatExo weight	2.55 kg
Maximum weight of user	80 kg
Anthropometry of user	
Percentiles	5th, 50th, 95th
Body parts	Thighs, calves, feet
Ratchet operating angle	
Inclination angle (degree)	90, 72, 54, 36, 18

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2.4. Fabrication Process

Once the three-dimensional computer models of the SolatExo were finalized, they provided detailed specifications for the fabrication phase. The profiles and dimensions of the SolatExo components, including length, width, hole diameter, and fillet edge, were sketched in CAD software. For prototyping purposes, the base material of the SolatExo was aluminum sheets with a thickness of 3 mm. The CAD file was then sent to a laser-cutting machine to cut the desired profile based on the dimensions. Angled shapes of the components were bent using a hydraulic bending machine.

To support weak knees, the SolatExo incorporated a mechanical ratchet (see Table 2, part no. 3), purchased rather than fabricated for cost efficiency. This steel ratchet connects the upper and lower structures, facilitating controlled movement and providing stability during sit-stand and stand-sit transitions. Positioned near the knees, the ratchet mimics the knee joint by limiting movement in one direction. This reverse circular ratchet engages its toothed components with a circular track to prevent undesired rotation, ensuring stability in specific postures. This is particularly useful during movements from standing to sitting, where control and safety are critical.

The components were connected using rivets, bolts, and nuts. After assembly, two fitted sleeves, similar to pockets, were stitched to the left and right sides of the trousers to securely attach the upper part of the SolatExo prototype to the thigh. Additionally, elastic straps are used to fasten the lower part of the exoskeleton to the ankles, reducing strain on the thighs and calves and improving overall comfort. Once the components were seamlessly integrated into the trousers, the researchers invited a volunteer to wear and experience the SolatExo. An iterative process was then undertaken to position the components and trousers to ensure that the SolatExo is comfortable to wear and does not disrupt the user's natural movements.

A SolatExo prototype was fabricated for Salah to demonstrate kinematic compatibility by seamlessly mirroring the natural movements of the human body during Salah, including standing upright (qiyam), bowing, prostration, and sitting during the last tashahhud, as shown in Fig. 3. This involves aligning the SolatExo's joints precisely to the user's hips, knees, and ankles, ensuring a harmonious interaction. The importance of kinematic compatibility in exoskeleton use for Salah lies in its ability to enhance the user's experience by providing support and alignment during the Salah movements. By accurately replicating the biomechanics of the lower limbs and incorporating anthropometric alignment with the user, the SolatExo promotes a fluid and comfortable prayer experience, allowing individuals to engage in their Salah with ease and confidence.

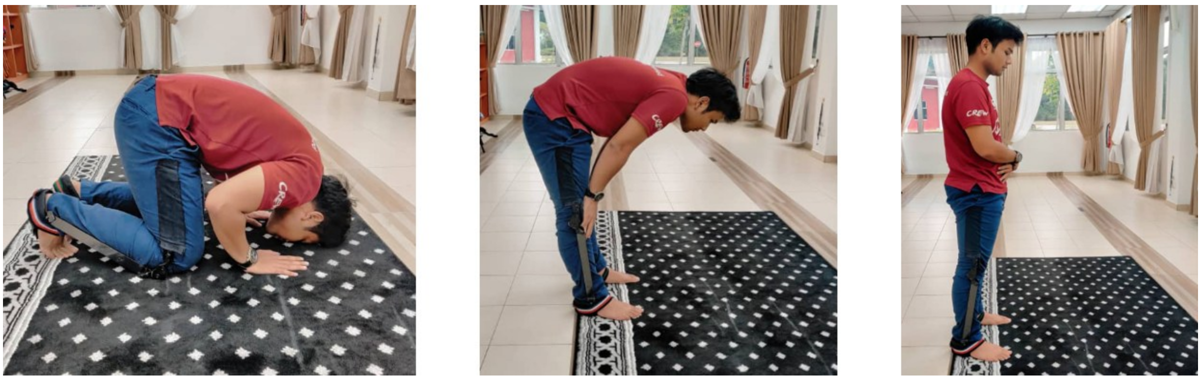

Figure 3. Prostration, bowing and standing using SolatExo prototype

2.5. Range of Motion (ROM) Assessments

After the fabrication process was completed, the physical prototype of the SolatExo underwent thorough range of motion (ROM) assessments to determine its effectiveness in supporting and facilitating essential movements during Salah. These assessments utilized a Jamar goniometer (Sammons Preston, USA), as illustrated in Fig. 4, to ensure the SolatExo was properly configured and fitted for each user. The evaluations involved five healthy male participants aged 20 to 30 years, whose body dimensions were meticulously measured to customize the SolatExo's positioning for optimal alignment and movement during Salah. The focus of the assessment was on the main joint movements critical to the Salah sequences, including trunk flexion and abduction, knee flexion and extension, as well as ankle dorsiflexion, plantar flexion, and supination. The ROM measurements were adapted from the techniques described by Rabin and Kozol [10].

Figure 4. Range of motion assessments using a goniometer

2.5. Muscle Contraction Analysis

Following the ROM assessments, a detailed muscle contraction analysis was performed to quantify the muscle activity required using the SolatExo during various Salah movements. This analysis aimed to ensure that the exoskeleton provided adequate support without overexerting the user. Employing an electromyography (EMG) instrument (Delsys Trigno wireless EMG, USA) depicted in Fig. 5, the study analyzed muscle contractions of participants during Salah. The same five male subjects from the ROM assessments were recruited for consistency. The EMG experiment was structured into three phases for each participant: first, to establish the maximal voluntary contraction (MVC) as a baseline for maximal muscle activity; second, to measure muscle contractions without the use of the SolatExo; and finally, to evaluate muscle contractions while wearing the SolatExo during Salah. Targeted muscles included the vastus medialis, vastus lateralis, rectus femoris, tibialis anterior, and soleus on both legs. This methodical approach, repeated thrice for each participant, aimed to yield empirical insights into the SolatExo's influence on muscle contraction during Salah. The total duration of the EMG experiment was approximately 10 minutes, capturing complete movement cycles associated with Salah, thereby providing a comprehensive understanding of muscle engagement and exoskeleton efficacy. The EMG measurement protocols and signal processing techniques were adapted from the past study [11].

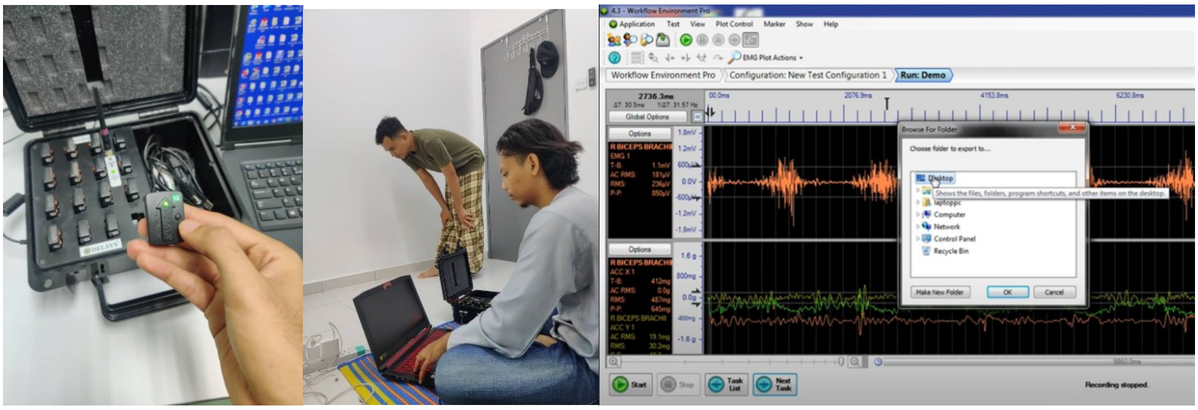

Figure 5. Muscle contraction analysis using EMG instrument

2.7. Usability Study

After completing the muscle contraction analysis, a usability study was conducted to gather user feedback on SolatExo's performance during real-world Salah scenarios. The system usability scale (SUS) was applied to assess SolatExo's ease of use, functionality, and user experience. The SUS consists of 10 statements that evaluate many facets of usability, including user pleasure, learnability, efficiency, and simplicity of use [12]. Users indicate how much they agree with each statement on a Likert scale (Strongly Disagree, Neutral, Agree, Strongly Agree). Statement 1: I would like to use this SolatExo to assist me in Salah. Statement 2: I found this SolatExo is complicated. Statement 3: I found the SolatExo to be simple to operate. Statement 4: I think I would need assistance to use this SolatExo. Statement 5: I noticed that this SolatExo has many useful functions. Statement 6: I think the design is too weird. Statement 7: I would expect that people who have a physical disability would quickly learn how to use this SolatExo to perform Salah. Statement 8: I found this SolatExo to be very difficult to operate. Statement 9: I feel comfortable when using this SolatExo. Statement 10: I need to learn many things before using this SolatExo. The usability of the SolatExo was assessed at before, during, and after wearing this exoskeleton.

2.8. User Experience Testing

Following the usability study, the researchers tested SolatExo's user experience. This testing involved two participants who had sustained knee injuries from road accidents, ensuring that the assessment focused on individuals who could benefit from the device. Each participant was equipped with the SolatExo while performing Salah, allowing for a practical evaluation of the exoskeleton's functionality and comfort during the Salah movements. The testing environment was structured to simulate a typical Salah setting, enabling participants to engage in the full range of movements, including standing, bowing, and prostration. Feedback was gathered through direct observation and interviews, focusing on comfort, ease of movement, and overall satisfaction with the SolatExo during the Salah experience. This methodology aimed to gain insights into how well the exoskeleton supported natural body movements and alleviated discomfort associated with knee injuries, ultimately informing further refinements to the design and functionality of the SolatExo.

2.9. Experimental Procedures Approval and Statistical Analysis

The experimental procedures were reviewed and approved by the Research Ethics Committee of UTeM. Both descriptive statistics and the inferential tests were conducted using Minitab software. Descriptive statistics were performed on the ROM angles and the root mean square values of muscle contraction to summarize the central tendency and variability of the data. The minimum, mean, and maximum were calculated for each measure to provide an overall view of the data distribution and to facilitate comparison across conditions, i.e., with and without the SolatExo.

A paired sample t-test was applied to compare the trunk, knee, and ankle ROM between wearing and not wearing the SolatExo. This parametric test was chosen because it evaluates the differences in ROM across two related conditions (with and without the exoskeleton) and is appropriate when the data are normally distributed. The t-test determines whether the mean difference in ROM between the two conditions is statistically significant, thus enabling the assessment of the impact of the SolatExo on joint movement.

Before conducting the paired t-test, the normality of the data was assessed using the Shapiro-Wilk test. This test was selected due to its high power for detecting deviations from normality, especially with small to moderately sized datasets, ensuring that the parametric assumptions of the t-test were met. A significance level (α) of 0.05 was used as the threshold for normality. When the p-value from the Shapiro-Wilk test exceeded 0.05, the data were considered normally distributed, justifying a parametric test.

3. RESULTS

3.1. User's Requirements

112 respondents took part in the questionnaire survey of user requirements. 59.8% and 40.2% for male and female, respectively. The age is 18 years and below (29.1%), 19 to 29 years (48.2%), 30 to 39 years (10.9%), and 40 and above (11.8%). Fig. 6 reveals the factors influencing the decision to deploy the SolatExo. The majority of respondents, comprising 87.5%, prioritize functionality, indicating a strong emphasis on the practical benefits and features of the SolatExo. To meet this demand, the SolatExo design focused on several technical elements. Lightweight materials, such as aluminum, were used to ensure the device was not cumbersome, making it easier for users to move during Salah. The SolatExo also features a slim design to allow natural body movements without restrictions. Adjustability was incorporated to accommodate users of various sizes and physical needs, enhancing comfort and usability. Additionally, the design ensured portability, aligning with users' need for a practical and convenient solution. These functional requirements gathered from the survey were integral to shaping the final design, ensuring it addressed the specific needs of its target users.

Price emerges as the second most influential factor, with 57.1% of participants highlighting its significance, suggesting that cost remains a substantial consideration in decision-making. Durability and lasting performance also hold weight, as indicated by 49.1% of respondents. Aesthetics and appearance appear in the provided data, with 47.3% of respondents expressing their influence on the decision, emphasizing the importance of the SolatExo visual appeal alongside its functional attributes. Usability, mentioned by 47.3%, complements the focus on functionality, indicating that ease of use is critical for potential buyers. Overall, these insights underscore the multifaceted nature of the decision-making process, incorporating aspects of cost, functionality, durability, and aesthetics into potential users' considerations.

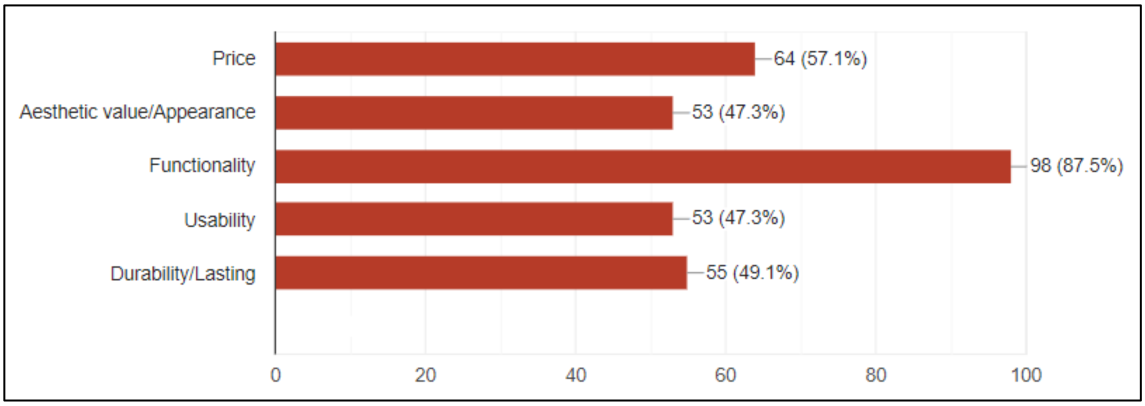

Figure 6. Factors influencing the decision to deploy the SolatExo

3.2. Range of Motion (ROM)

In this study, the ROM was analyzed to determine if there were any significant differences in joint movements while wearing and not wearing the SolatExo. Table 4 compares the ROM while wearing and not wearing the SolatExo. The p-values were obtained through a paired sample t-test, which compared the minimum and maximum joint angles between both conditions. The obtained p-values for minimum and maximum joint movements at a significance level of 0.05 reveal that, generally, there are no statistically significant differences in most of the examined parameters. Specifically, for minimum values, no significant differences are observed in trunk flexion, trunk abduction, knee flexion, ankle dorsiflexion, ankle plantar flexion, and ankle supination, with p-values ranging from 0.142 to 0.674. Similarly, for maximum values, trunk flexion, trunk abduction, knee flexion, and knee extension show no significant differences, with p-values ranging from 0.108 to 0.602.

However, significant differences were found in ankle plantar flexion ($p = 0.006$) and ankle supination ($p = 0.001$), indicating a potential restriction in movement for these joints. These results highlight that, although the SolatExo maintains standard movement patterns for most joints, improvements in ankle movement design could be beneficial. This limitation aligns with existing literature, where studies on passive exoskeletons often report restricted ankle movement due to the device's design. For instance, Chang [13] found that while exoskeletons are effective in recycling energy, they may limit ankle joint movement, especially during push-off phases. This restriction can impact the natural gait cycle and mobility, which is crucial for ensuring the exoskeleton does not hinder essential movements such as those in Salah. In light of these findings, improvements in ankle movement design for the SolatExo could enhance functionality, particularly in maintaining a natural ROM. The VS-AnkleExo, for example, highlights the significance of compliant actuators that adjust to user movements, which could alleviate some of the restrictions observed in traditional exoskeleton design [14]. By incorporating more adaptable components, the SolatExo could allow smoother transitions between standing, sitting, and prostration, which are vital movements in Salah.

Furthermore, optimizing ankle torque in exoskeletons has been shown to improve metabolic efficiency, particularly at varying speeds of movement, such as walking or transitioning between postures [15]. Applying these principles to the SolatExo could mitigate the current limitations in ankle movement and enhance user comfort and efficiency during key movements in Salah. Additionally, adjustable stiffness in the actuators could allow for more natural movement patterns, further enhancing user satisfaction and reducing discomfort during complex joint angles [14].

In general, the results mentioned above collectively suggest that, at the 0.05 significance level, most observed variations in joint movements are not statistically significant, signifying overall consistency in the measured parameters. However, refining the ankle mechanism through these design improvements could significantly increase its overall effectiveness, particularly for users who need more flexibility and comfort in ankle-related movements during Salah.

Table 4. Comparisons of range of motion among five subjects while wearing and not wearing the SolatExo

Joints	Movement	Without SolatExo (angle, °)		With SolatExo (angle, °)		Percentage Reduction of ROM		P-value (significance level of 0.05)	
		Min (°)	Max (°)	Min (°)	Max (°)	Min (%)	Max (%)	Min	Max
Trunk	Flexion	7	90	6	87	14.29	3.33	0.574	0.526
	Abduction	4	18	4	16	0	11.11	0.577	0.108
Knees	Flexion	6	160	6	152	0	5	0.674	0.602
	Abduction	5	15	3	14	40	6.67	0.145	0.515
Ankles	Dorsiflexion	5	20	4	19	20	5	0.142	0.621
	Plantar Flexion	5	27	4	23	20	14.81	0.246	0.006
	Supination	3	32	3	27	0	15.63	0.621	0.001

3.3. Muscle Contraction

Results of EMG for Subject 1 in Fig. 7 varying impacts of SolatExo on different muscles during performing Salah movements. Notably, the rectus femoris muscles on both left and right show a higher percentage without wearing the SolatExo, suggesting an increased effort during those movements. With the SolatExo, these percentages decrease, indicating a positive effect in reducing muscle activity. Similarly, the tibialis anterior and soleus muscles, particularly on the left side, exhibit higher percentages without the SolatExo, implying increased muscle effort. However, with the SolatExo, these percentages decrease, suggesting potential support and alleviation of muscle load during the movements.

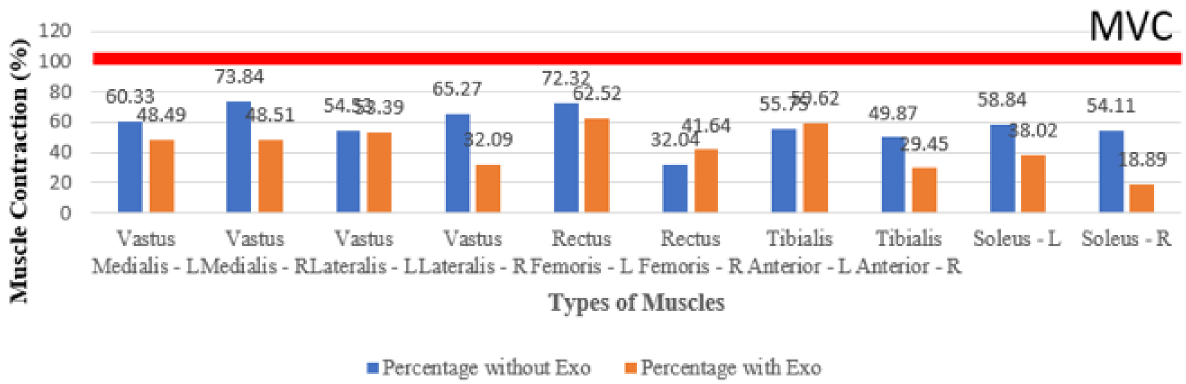

Figure 7. Percentage difference between the actual muscle contraction and the maximum voluntary contraction (MVC), with and without SolatExo, for subject 1

For Subject 2 as shown in Fig. 8, the EMG analysis reveals varied muscle activity with and without the SolatExo during Salah movements. The vastus medialis muscles on both sides exhibit higher percentages with the SolatExo, suggesting increased engagement during the movements. Similarly, the vastus lateralis muscles, particularly on the left, show higher percentages with the SolatExo, indicating elevated muscle activity. The rectus femoris muscles on both sides also display higher percentages with the SolatExo, suggesting increased effort. Conversely, the tibialis anterior and soleus muscles exhibit lower percentages with the SolatExo, implying a potentially positive impact on reducing muscle load. Overall, the findings suggest that while the SolatExo might increase engagement in specific muscles, it may contribute to alleviating the load on others, particularly the tibialis anterior and soleus muscles during the salah movements.

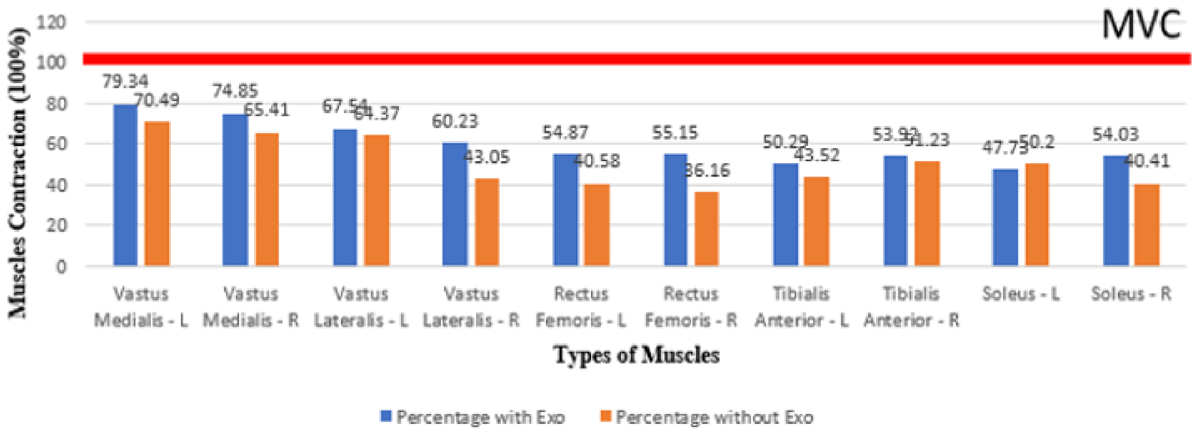

Figure 8. Percentage difference between the actual muscle contraction and the maximum voluntary contraction (MVC), with and without SolatExo, for subject 2

Subject 3's muscle activity assessment, both with and without the SolatExo during Salah movements, unveils distinctive patterns as shown in Fig. 9. The vastus medialis muscles present dissimilar responses, with the left exhibiting increased engagement when assisted by the exoskeleton, while the right experiences a reduction. Similarly, the vastus lateralis muscles, particularly on the left, display heightened contraction without the SolatExo, which diminishes with its use. The rectus femoris muscles on both sides show decreased activity with the exoskeleton, indicating potential relief. However, the tibialis anterior and soleus muscles manifest elevated percentages with the SolatExo, suggesting an augmented demand on these muscles during the movements.

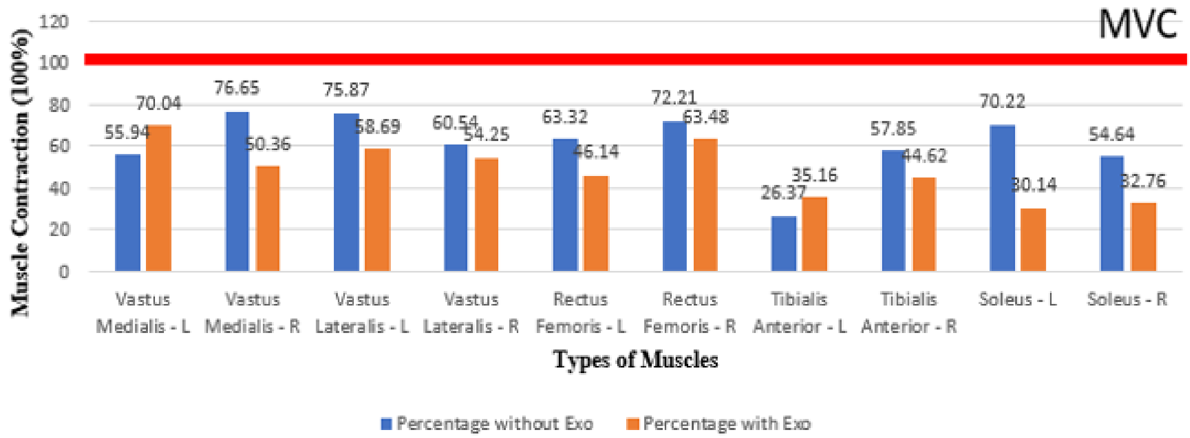

Figure 9. Percentage difference between the actual muscle contraction and the maximum voluntary contraction (MVC), with and without SolatExo, for subject 3

Subject 4's muscle activity analysis during Salah movements, with and without the SolatExo, suggests varied impacts. The rectus femoris muscles on both sides exhibit notably higher percentages with the SolatExo, indicating increased demand on these muscles when assisted, as illustrated in Fig. 10. Conversely, the vastus medialis and vastus lateralis muscles, particularly on the left side, show decreased contraction of the SolatExo, suggesting potential relief from muscular engagement. The tibialis anterior muscles demonstrate reduced activity with the exoskeleton, indicating potential support in minimizing muscle load. However, the soleus muscles on both sides manifest higher percentages with the SolatExo, implying increased engagement during the Salah movements.

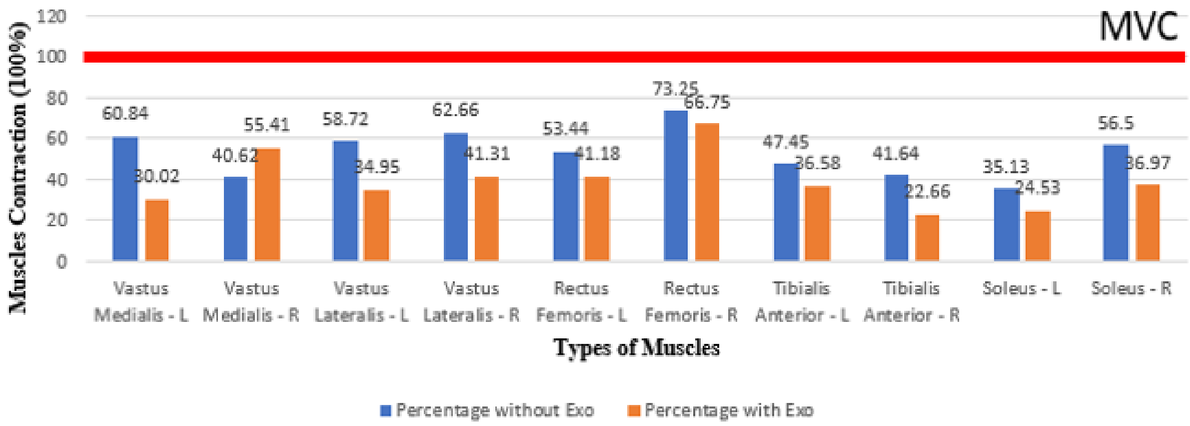

Figure 10. Percentage difference between the actual muscle contraction and the maximum voluntary contraction (MVC), with and without SolatExo, for subject 4

Subject 5's muscle activity comparison during Salah movements, with and without the SolatExo, reveals distinct patterns, as depicted in Fig. 11. The rectus femoris muscles on both sides display substantially higher percentages without the SolatExo, indicating increased engagement. In contrast, the vastus medialis and vastus lateralis muscles, particularly on the left side, demonstrate decreased activity with the SolatExo, suggesting potential relief from muscular strain. The tibialis anterior muscles exhibit relatively consistent percentages with and without the SolatExo. In contrast, the soleus muscles, particularly on the right side, show a notable reduction in contraction with the SolatExo.

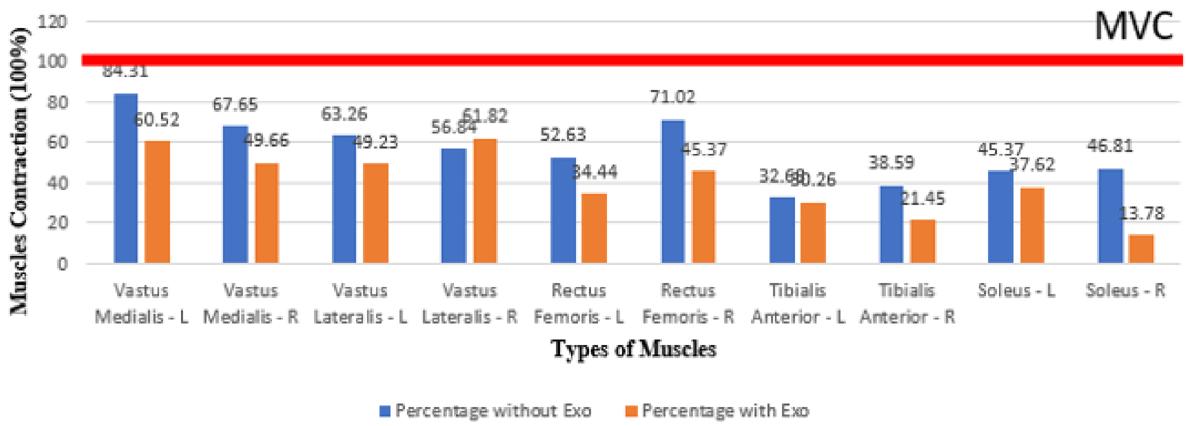

Figure 11. Percentage difference between the actual muscle contraction and the maximum voluntary contraction (MVC), with and without SolatExo, for subject 5

The high muscle contraction values observed during Salah (Fig. 7 till Fig. 11), particularly in the vastus medialis, vastus lateralis, rectus femoris, tibialis anterior, and soleus muscles, reaching 70%-80% of MVC, indicate significant muscle engagement in healthy individuals performing these movements. Since all participants in this study were healthy, their ability to achieve such high activation levels can be attributed to their physical conditioning, enabling more efficient recruitment of muscle fibers during physical activity. These high contraction levels are not sustained throughout Salah but are concentrated during specific movements or postures that place increased demands on these muscle groups, such as transitioning from standing to prostration or rising from kneeling to standing.

The literature supports these findings. The vastus medialis and vastus lateralis, crucial for maintaining stability during standing and knee flexion, exhibit notable EMG activity during Salah (Rabbi et al., 2019) [16]. These muscles play a pivotal role in stabilizing the knee during flexion and extension, which is necessary for the smooth execution of Salah postures. Similarly, the rectus femoris shows significant activation during transitions between postures, such as kneeling or bowing during prayer [16]. These transitions require strong quadriceps engagement to support body weight and maintain posture.

Additionally, the tibialis anterior and soleus muscles are essential for maintaining ankle stability and control during Salah. These muscles, responsible for dorsiflexion and plantar flexion of the foot, help stabilize the ankles during various prayer positions, especially during movements like bowing and standing [17]. Their activation ensures balance and stability, particularly when transitioning between different postures.

Moreover, these muscle activation patterns are not unique to Salah but are also seen in similar physical activities, such as squatting. Studies show that the quadriceps muscles, including the rectus femoris, vastus lateralis, and vastus medialis, exhibit high EMG activity during squatting [18]. This suggests that Salah, particularly the transitions between its standing and kneeling postures, places similar biomechanical demands on the lower limbs, explaining the high contraction levels observed.

While the SolatExo users in this study demonstrated muscle contraction values reaching 70%-80% of MVC, such values are reasonable given Salah's physiological demands and parallels with other high-demand movements like squatting. These high activation levels highlight the importance of lower limb muscle strength and coordination during Salah, especially during critical moments of transition between postures. However, as these contraction levels are concentrated in specific phases of the prayer, future designs of assistive devices like SolatExo should focus on supporting these high-demand movements to reduce the physical effort required.

3.4. Usability of the SolatExo

In this study, the usability of the SolatExo was evaluated using the SUS, a widely accepted tool for measuring the usability of a system or product. The SUS score was calculated following the standard methodology described by the SUS's founder [12]. To derive the usability score, each participant's responses were processed as follows: for the odd-numbered questions (Q1, Q3, Q5, Q7, Q9), one point was subtracted from the participant's rating. The participant's rating was subtracted from five for the even-numbered questions (Q2, Q4, Q6, Q8, Q10). This adjustment aligns the scoring so that higher scores consistently reflect better usability. The adjusted scores for each question were then summed to obtain a total score for each participant. This total score was multiplied by 2.5 to convert it to a scale from 0 to 100, representing the individual SUS score.

The average score was computed after calculating the SUS scores for all participants. In this study, the final mean SUS score was 68, indicating a moderate to good level of usability for the SolatExo. According to the SUS interpretation scale, scores between 62.7 and 72.5

reflect “Good” usability, while scores above 72.6 indicate “Excellent” usability. A score below 62.6 would indicate areas for improvement in usability.

3.5. User Experience

The user experience test involved two participants wearing the SolatExo while performing Salah. The outcomes of this test include feedback on usability, comfort, performance, safety, and overall user experience. Their feedback is summarized in Table 5. These user experience feedbacks provided important insights into both the strengths and challenges of the SolatExo. A key pattern that emerged from the two participants, who had knee injuries from road accidents, is that they found the SolatExo helpful but not without its difficulties. Both users reported that the SolatExo improved their ability to perform standing prayers, suggesting that the exoskeleton succeeded in providing the necessary physical support during this posture of Salah. However, they also both noted discomfort when sitting between prostrations and during the final tashahhud, which points to an area where the design could be improved. This discomfort likely stems from the structural rigidity of the SolatExo, which may not have adequately supported more nuanced, seated positions required during Salah.

Usability was another aspect that presented challenges. User 1 found the SolatExo “very difficult to operate,” while User 2 needed more time to learn how to use the device. This feedback highlights that the ease of use could be improved through more intuitive design or better user instructions. Simplifying the adjustment mechanisms or enhancing the interface for adjusting the exoskeleton could make the device more user-friendly, especially for individuals who may not have extensive technical experience.

Both participants indicated that the SolatExo did not pose any safety risks, a positive outcome regarding the device’s design integrity. Despite the challenges noted, the overall user experience was relatively positive. User 2 expressed delight in using the device, finding it unique and helpful. Although user 1 acknowledged that the device was challenging, still derived some pleasure from it. This indicates the value in the SolatExo, but refinements are needed to improve user comfort and ease of operation.

In future designs, these insights suggest a need to focus on improving the SolatExo’s ergonomics features, particularly for seated positions in Salah, and on simplifying the usability of the device. A more flexible structure that can accommodate the dynamic shifts between standing, bowing, and sitting postures would enhance user comfort. Additionally, providing clearer instructions or developing a more intuitive design could improve user satisfaction and operational efficiency.

https://doi.org/10.31436/iiumej.v26i1.3430

Table 5. Feedback from the end users after using SolatExo

End-user	Physical Injuries	Feedback after using SolatExo
User 1	 Knee injury due to road accident	Usability: I found the SolatExo to be very difficult to operate. Comfort: Sitting between the two prostrations and the final tashahhud is uncomfortable. Performance: I feel it helps me get up a bit. Safety: I do not feel that it can harm me when using it. Overall user experience: It's challenging to use, but I still find pleasure in using it.
User 2	 Knee injury due to road accident	Usability: I need time to learn how to use it. Comfort: It is a bit uncomfortable sitting during the two prostrations and the final tashahhud. Performance: It can help me to perform standing prayers without relying on a chair. Safety: It can help me to perform standing prayers without using a chair. Overall user experience: Overall user experience: I feel delighted using it because it is rarely found.

4. DISCUSSION

4.1. Design Requirements

Table 6 outlines the essential design requirements for the SolatExo, tailored to enhance its usability and effectiveness during Salah. The specified physical dimensions and geometry of the main frame and ratchet ensure a lightweight, slim design that integrates seamlessly with the user's body, facilitating natural movements. Performance characteristics include a maximum sustained load capacity of 100 kg and adjustable operating angles (90°, 72°, 54°, 36°, 18°) to support dynamic postures during prayer. Materials such as lightweight aluminum, rubber for comfort, and flexible polyester and nylon contribute to durability and user comfort. User-centric considerations encompass price, aesthetics, functionality, usability, and durability, ensuring the exoskeleton meets diverse user needs effectively. Environmental requirements focus on corrosion resistance, recyclability of materials, and durability against wear and tear, promoting sustainability and long-term usability in various environments.

Table 6. Design requirements of SolatExo

Design Requirements	Specifications	Justification
Physical dimension/ geometry	Main structure: • Length: 760 mm • Width: 50 mm • Thickness: 3 mm Ratchet: • Operating angle: 5 gears of adjustable level, maximum to 90° • Length: 150 mm • Width: 15 cm	The SolatExo is designed to match the anthropometry requirements, considering users at the 5th percentile for short users, the 50th percentile for medium-tall users, and the 95th percentile for tall users.
Performance characteristic	Maximum sustained load: • 80 kg Range of motion: • 90°, 72°, 54°, 36°, 18°	These features directly impact SolatExo's ability to provide effective support during various activities, accommodating dynamic movements and sustaining loads without compromise.
Materials	• Aluminum sheet • Rubber • Polyester • Nylon	The aluminum is lightweight and strong, providing necessary support without hindering mobility. Rubber ensures user comfort during movement. Polyester and nylon securely support various parts of the SolatExo while allowing for flexibility.
User needs	• Price • Aesthetic • Functionality • Usability • Durability	The user-centric aims to offer optimal support and comfort. By tailoring the technology to an individual's specific needs and lifestyle, the SolatExo enhances mobility, addressing unique considerations and empowering the user to move with greater ease and independence.
Environmental requirements	• Resistance to corrosion • Material recyclability • Wear and tear	These considerations ensure the device remains durable and reliable across different environments while adhering to sustainable practices. Incorporating these features results in an environmentally friendly, long-lasting solution tailored to individual needs, promoting enhanced mobility and an improved overall quality of life.

4.2. Range of Motion

Body movements are crucial in prayer, as noted by [19]. The development of lower limb exoskeletons now includes multiple degrees of freedom to accommodate a range of motions guided by user intentions, such as transitions from sitting to standing, standing to sitting, and even walking [20]. Recent advancements in exoskeleton technology have improved joint mobility and range of motion, which has been beneficial for various applications such as therapeutic interventions and motion analysis [21]. Moreover, exoskeletons are now being engineered with innovative actuation techniques and variable stiffness actuators. This allows for natural joint movement and tailored support based on the user's level of impairment [22],

[23]. These design advancements enhance the functionality and adaptability of exoskeletons, supporting users with physical disabilities in their daily activities, including prayer.

Incorporating SolatExo into Salah presents unique challenges regarding ROM and physical dimensions. SolatExo, while intended to enhance mobility, may restrict crucial movements required for proper Salah postures, such as kneeling and prostration, potentially impacting the overall Salah experience. This is consistent with findings in exoskeleton-assisted gait training, where limitations in joint ROM [24] and altered gait patterns have been observed [25]. Additionally, the added weight and bulkiness of SolatExo may disrupt Salah's flexibility and tranquility. However, in this study, the SolatExo is designed to be adjustable to accommodate a wide range of physical dimensions, including users at the 5th percentile for short users, the 50th percentile for medium-tall users, and the 95th percentile for tall users. By prioritizing inclusivity and accessibility, these advancements aim to ensure that users can perform their Salah with dignity and ease despite physical limitations. Therefore, integrating exoskeletons into Salah contexts requires a careful balance between technological assistance and Salah movements to uphold the sanctity of these practices.

The analysis of ROM in this study revealed no significant differences in most joint movements when comparing participants wearing the SolatExo to those without it, except for ankle plantar flexion and supination, where significant restrictions were observed. These findings suggest that while the SolatExo maintains the normal movement patterns of key joints like the knees and trunk, its design may restrict ankle movements, particularly during dynamic phases of Salah. This is critical since ankle flexibility is vital in maintaining balance during postures such as standing and bowing. The restricted ROM in ankle plantar flexion and supination aligns with findings in similar passive exoskeletons, where ankle movement is often constrained due to the structural design of the device. For instance, Chang [13] reported limitations in ankle joint flexibility in passive exoskeletons designed for rehabilitation, where energy recycling mechanisms inadvertently limited natural movement. Passive devices often lack the adaptive mechanisms present in active exoskeletons, which can modulate joint stiffness and allow for more natural movement patterns [15].

Future iterations of SolatExo could integrate adjustable mechanisms that allow for a greater range of plantar flexion and supination without sacrificing structural support to improve ankle flexibility. As demonstrated in the VS-AnkleExo [14], adjustable stiffness components could provide the necessary balance between stability and freedom of movement, thus enhancing the overall functionality of the SolatExo for Salah performance. These improvements would allow for a more natural execution of postures that require full ankle mobility, such as during prostration and sitting between the two prostrations.

4.3. Muscle Contraction

Previous studies have applied EMG to analyze muscle contraction patterns during different Salah movements, such as standing, bowing, prostration, and sitting [26], [27], [28]. However, none of these studies involved participants wearing an exoskeleton. Investigating the impact of passive exoskeletons (e.g., SolatExo) on muscle contractions during the Salah movements reveals complex dynamics between technological assistance and physiological responses. While exoskeletons are engineered to assist users in their movements, their impact on muscle activity during Salah represents a crucial yet understudied aspect. A study focusing on the forward bending movement has shown that the passive Laevo exoskeleton alters muscle activation patterns, resulting in reduced contraction in the lumbar/back (erector spinae muscles); however, concerns arise regarding potential weakening of the lumbar musculature due to prolonged exoskeleton use [29]. Similarly, when applied to the context of Salah, the exoskeletons may attenuate muscle contractions necessary for maintaining proper prayer postures, such as kneeling and prostration.

Previous studies have applied EMG to analyze muscle contraction patterns during different Salah movements, such as standing, bowing, prostration, and sitting [16], [17]. However, none of these studies involved participants wearing an exoskeleton. Investigating the impact of passive exoskeletons, like SolatExo, on muscle contractions during Salah reveals complex dynamics between technological assistance and physiological responses. While exoskeletons are designed to support users during movement, their influence on muscle activity during Salah represents a critical but understudied area.

The EMG experiments show that the SolatExo exerts varied effects on muscle activity during Salah movements. For instance, the vastus medialis reached up to 80% of MVC, which, while appearing elevated, is consistent with the demands placed on the lower limbs during Salah postures. This high activation level is particularly evident during movements requiring significant stabilization, such as rising from prostration, where the quadriceps and knee extensors are engaged to support the body [16]. Muscles like the rectus femoris showed decreased contraction while using the SolatExo, suggesting that the exoskeleton alleviates muscular effort in some areas. However, the tibialis anterior and soleus, responsible for ankle stability and control, exhibited greater contractions when using the SolatExo. These muscles are crucial for maintaining balance during standing, bowing, and transitions in Salah, where the ankle joints must compensate for any external support, potentially leading to increased activation [17].

The results indicate that while the SolatExo provides structural support to certain muscle groups, it also imposes additional demands on others, particularly those involved in ankle stability. This finding is comparable to studies in squatting and similar activities, where the quadriceps, including the vastus medialis and vastus lateralis, exhibited high EMG activity [18]. Thus, while elevated in some muscles, the observed muscle activation patterns during Salah are within reasonable ranges for physical activities that involve complex postural transitions.

Note that the high muscle contractions observed in specific muscles are not consistent throughout the entire prayer but are more prominent during particular movements, such as transitioning from standing to prostration. These findings underscore the complex interplay between the SolatExo mechanisms and the dynamic requirements of Salah movements, where some muscles experience reduced effort. In contrast, others may face increased demands due to the nature of passive exoskeleton assistance. While passive exoskeletons, including the SolatExo, aim to reduce muscular strain, they may not actively assist movements as powered exoskeletons do. The high activation levels observed in muscles like the tibialis anterior and soleus highlight the need for further design improvements in the SolatExo. Incorporating adjustable or semi-active mechanisms could alleviate excessive muscle activity, particularly in the ankle joints, thus enhancing the device’s overall effectiveness for assisting Salah's movements, especially for individuals with physical disabilities. Further research is needed to optimize SolatExo for specific postures, ensuring personalized and effective assistance during Salah.

4.4. Usability

Examining the usability of SolatExo for Salah reveals multifaceted considerations at the intersection of technology and religious practice. While SolatExo aims to enhance mobility and support users’ movements, their integration into the context of the Salah movement presents unique challenges. Research on exoskeleton-assisted activities has highlighted usability concerns [30], such as comfort, ease of use, and adaptability to specific activities. When applied to Salah, users may encounter difficulties achieving the precise postures and movements required for prayer due to the constraints imposed by the SolatExo's structure. Additionally, the added weight and bulkiness of the device could hinder users' ability to seamlessly transition between Salah positions, potentially disrupting the flow and concentration essential for spiritual engagement. Optimizing the usability of SolatExo for Salah necessitates a holistic approach that considers both technological functionality and the user's cultural and religious practices. Emphasizing user-centered design principles is crucial to ensure a harmonious integration of technology into the ritualistic experience. Regarding technological design, kinematic compatibility [31] between the passive exoskeletons and users plays a significant role. For example, the mechanisms of gears and ratchets should allow smooth transitions of body postures. Furthermore, usability concerns include the ease of donning and doffing the exoskeletons, which requires careful study to ensure user comfort.

4.5. User Experience

Exploring the user experience of wearing SolatExo during Salah unveils intricate interactions between technology and religious devotion. While exoskeletons are engineered to enhance mobility and support users' movements, their integration into Salah practices introduces novel considerations. Research on user experience in assistive technology highlights the importance of comfort, usability, and perceived effectiveness [32], [33]. During Salah, users may perceive disruptions in the seamless flow of movements due to the exoskeleton's design, potentially impacting their overall satisfaction. Additionally, individual preferences and cultural sensitivities influence the acceptance and adoption of exoskeleton technology within Salah practices.

Extraordinary accessories for Salah can create social reluctance, as users might feel self-conscious or fear judgment from others when using visible or bulky exoskeletons. Therefore, inconspicuous and aesthetically pleasing designs are essential. The exoskeleton should be as unobtrusive as possible, utilizing slim structures, neutral colors, and materials that blend with traditional clothing. Incorporating traditional design elements, such as fabrics and patterns commonly found in traditional attire, can help the device integrate seamlessly into the user's Salah attire. Offering color, material, and fit customization options can further enhance user experience and confidence. Educating users and their communities about the benefits and functionalities of the exoskeleton, with endorsements from community leaders and religious scholars, can also help reduce social reluctance and normalize the use of such technology. These considerations highlight the importance of designing exoskeletons that are functionally effective, culturally, and socially acceptable to users.

4.6. Contribution of Study

The study's findings significantly contribute to understanding various factors related to SolatExo, an exoskeleton prototype designed to assist Muslims with physical disabilities during Salah. Firstly, this study identified the essential features required by users for SolatExo and revealed the specific functionalities and design elements crucial for its effectiveness in aiding Salah's performance. Secondly, this study investigated the extent to which SolatExo reduces users' range of motion during Salah, providing insights into its biomechanical implications and potential benefits for users with limited mobility. Thirdly, the authors examined how SolatExo influences muscle contraction patterns in users during Salah, offering valuable information about its impact on user physiology and comfort. Additionally, this study explored users' perceptions of SolatExo's usability, considering its practicality and effectiveness in aiding Salah's performance. Lastly, the authors gathered specific feedback from users regarding SolatExo's functionality, comfort, and overall effectiveness in enhancing their Salah experience, contributing to the ongoing refinement and optimization of this innovative assistive technology.

5. CONCLUSION

This study addressed a critical challenge faced by Muslims with physical injuries, particularly in performing Salah, where conventional support methods like chairs present significant limitations. These include disrupting congregation alignment and impeding ease of movement and portability. The development of the SolatExo prototype aimed to overcome these challenges by offering a functional passive exoskeleton designed specifically for assisting in Salah. Evaluation of the SolatExo prototype revealed key findings; while range of motion (ROM) showed no significant difference between wearing and not wearing the exoskeleton, muscle contraction, as measured by EMG, indicated reduced effort with the SolatExo, suggesting potential benefits in muscle activity reduction during prayer movements. Usability testing yielded a moderate to good score (68 on SUS) across respondents, indicating favorable usability levels, although user feedback highlighted operational challenges during specific prayer postures.

Future research should focus on enhancing SolatExo's usability and user experience through iterative design improvements informed by user feedback. Addressing operational difficulties, such as comfort issues during transitions between prostration and sitting phases, is crucial. Additionally, integrating advanced ergonomics principles and materials to enhance comfort and ease of use could further optimize SolatExo's performance. Moreover, expanding the study to a larger and more diverse user group, including individuals with a broader range of physical abilities and preferences, would provide valuable insights for refining the SolatExo better to meet the diverse needs within the Muslim community. This interdisciplinary approach underscores the importance of collaborative efforts between biomechanics, assistive technology design, and religious studies to develop inclusive solutions that enhance accessibility and participation in religious practices for individuals with physical disabilities.

In terms of real-world implementation, future work should explore the integration of the SolatExo in mosques and religious spaces (e.g., muscle), where it could serve as a practical assistive device for Muslims with physical limitations. Collaborating with religious authorities (e.g. State Islamic Religious Council) and community leaders could facilitate the adoption of the SolatExo in these settings. Pilot programs in mosques could help test their usability in real-world conditions and gather further insights to inform design improvements.

Expanding this study to a larger and more diverse user group, including individuals with different physical abilities and preferences, will provide valuable data for refining the SolatExo to meet the diverse needs within the Muslim community. Ultimately, this interdisciplinary approach, combining biomechanics, assistive technology, and religious studies, aims to create inclusive solutions that enhance accessibility and participation in religious practices for individuals with physical disabilities.

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