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An assistive sleeping bag for children with autism spectrum disorder

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Abstract

Children suffering from autism spectrum disorder are often reported to encounter sleeping disorder several causes such as hypersensitivity as result of irregular brain and muscle functions. Disturbance in sleep affects not only their health but also daytime activities including the risk of other cognitive and behavioral impairments. Such hindrance in sleep have been demonstrated to treat therapeutically by measures like application of deep pressure touch and full body vibration which can be beneficially integrated into the sleeping environment such as on the textile-based platform around the bed. With such a vision, this pilot design project aimed to develop a smart textile based sleeping bag incorporated with sensors to detect awakening stage of the child and thereby actuating stimuli for assuaging the child to fall asleep. To serve the purpose, a micro-controllable body movement detection sensor, based on conductive yarns connected to a vibrating motor was prosperously embedded at the interior of the sleeping bag along with weighted slots to exert deep touch and soothing sensation in the form of wearable technology.

Keywords: Autism spectrum disorder, Sleeping disorder, Sensor, Actuator, Smart textiles, Sleeping bag, Wearable technology

Introduction

Autism spectrum disorder (ASD) is a neurodevelopment disorder and children suffering from it, amongst other difficulties, encounter problems with social interaction and communication (Malow et al. 2006), along with restricted behavior and several sensory processing problems, including challenges with modulating sensory inputs such as touch and sound. Sensory issues are related to abnormalities of the cerebellum in the brain that regulates and coordinates muscular activities; hence, children suffering from ASD are often hypersensitive. A study by Polimeni et al. (2005) indicated that 73% of the parents of children with autism reported that their children suffered from sleeping disturbances, which is thought to be a result of hypersensitivity (Kodak and Piazza 2008), causing regression in the child's development (Kotagal and Broomall 2012).

Due to delicate nature of these children, it is always preferable to address such sleeping disorders therapeutically rather than pharmaceutically. The sense of a human presence often helps the child to fall asleep (Kotagal and Broomall 2012). Thus, a system can be developed to sense the sleeping patterns of the child and to simultaneously provide stimuli similar to a human presence to maintain the sleeping state. The textile platform of the bed can be used to simulate such sensing and stimulus actuation. Such a smart platform can be constructed in the form of wearable technology whereby the textile substrate interacts with its surrounding environment and/or user, and consists of one or all of following three units: a sensor, an actuator, and/or a controller device (Stoppa and Chiolerio 2014).

The state of sleep can be identified by detecting the amount of bodily movement via a pressure-based sensor system. In addition, several stimuli replicating a human presence to the child, such as deep pressure and a vibrating motion (Grandin 1992; Bressel et al. 2011), can be mounted on the same system to provide a complete solution. However, no significant design development or integrated research was found to combine these technologies on a single platform to the best knowledge of this study. Thus, realizing the underlying necessity of addressing sleeping disorders within the scope of smart textiles, this study aimed to design an intelligent sleeping bag that would be able to detect bodily movements that indicate waking, and thus actuate artificial stimuli to help the child to fall asleep. The questions to be addressed in this pilot study are whether such a sleeping bag, integrated with several electronic and computing devices in the form of wearable technology, can deliver the designated performance while maintaining the basic comfort level for daily use. In addition, a sophisticated data-processing system and the developed design would need to satisfy the flexibility, durability, and ergonomic requirements via the textile platform. The idea of designing such a solution is depicted in this paper, together with material and operational details of the prototype construction to be finally validated via responses from human subjects. By using ubiquitous computing devices in the form of sensors, actuators, and microcontrollers embedded within the textile platform of the sleeping bag, this pilot study is believed to contribute to the further development of similar wearable technology.

Literature review

Parents have often been reported to assist their children on the bed to make them sleep, and it would seem that these children developed a need for external stimuli associated with their sleeping habits (Kotagal and Broomall 2012). This behavior indicates a need for an assistive environment around the child's bed that incorporates stimuli that are favorable for the sleeping sensation.

Deep pressure touch

A profound kind of touch, referred to as deep pressure touch, is perceived as relaxing and has been proven to have a calming effect on children with psychiatric disorders, such as ASD (Grandin 1992). In addition to a therapeutic history of using specially shaped jackets (Krauss 1987) to confine patients' movements, several research studies and commercial development reports have described the use of deep pressure sensations for the purpose of calming patient. Grandin (1984) described a device that provided lateral pressure when the user lay down inside of it. The soft, padded inner surface of the hardboard-based device was constructed in a V-shape to support the entire body with option for the user to regulate the amount of pressure to be applied. A later evaluation of the actual machine, called the "squeeze machine", among normal adult college students suggested it provided sensations such as "relaxing" or "sleep" (Grandin 1992).

In this study, the "squeeze machine" was used on children with a neurodevelopmental history at six different therapeutic facilities, and was reported to be beneficial for disorders related to hyperactivity. Later, Krauss (1987) described the development of a sleeping bag-like assembly by sandwiching users between two air mattresses with possibility of exerting circumferential pressure from all directions by pulling a strap around them. The subjects used to evaluate the system were chosen from groups of normal college students who showed different levels of anxiety based on a questionnaire. A subjective analysis of the subjects' responses indicated an improvement in the relaxed state when pressure was exerted on them for a specific duration in a confined environment.

Weighted vest and blanket

A similar approach to providing deep pressure through clothing has been applied in the form of a vest or blanket that consists of about 10% of the wearer's weight by weighing the pockets and distributing the weight evenly along the user's body. Certified pediatric therapists have reported that the vest helps children who have been diagnosed with ASD to maintain calm and to increase their attention (Olson and Moulton 2004). Fertel-Daly et al. (2001) studied the weighted vest's effectiveness on motor activity. After wearing it for one and a half to 2 h, the participants showed less distraction and self-stimulatory activities. A similar study by Myles et al. (2004) using the same weight level and various durations of wear revealed a mean increase in task time and a decrease in self-simulation. A reduced amount of weight (5% of the wearer's body weight) and wear time (5 min) also showed positive effects on children's behavior (VandenBerg 2001).

Weighted blankets are another method of applying deep pressure treatment through textiles based on a similar principle to the weighted vest. Gringras et al. (2014) conducted a study to determine the effectiveness of these commercially available blankets (Mosaic Weighted Blankets, n.d. and "Weighted Blankets," n.d.) on the subject children by recording their total sleep time, and reported no significant effect on the sleep duration or quality. However, the children and the parents in the study favored the use of the weighted blanket over normal ones. However, an extensive study measuring the heart rate and electrodermal activity of the patient suffering from anxiety and covered with a weighted blanket revealed more beneficial aspects (Chen et al. 2013). A study using similar measurement techniques but employing a 30-pound weighted blanket on adult subjects suffering acute inpatient showed an effectiveness rate of about 63% in reducing anxiety levels, and a 78% preference for inducing a calming environment (Mullen et al. 2008). Vital sign metrics in these studies concluded the blankets to be safe for daily use (Chen et al. 2013; Mullen et al. 2008). A number of guidelines and recommendations for the use of these weighted products for clinical purposes, such as treating ASD, can be found at the National Guideline Clearinghouse database of the U.S. Department of Health and Human Services ("Use of a weighted or pressure device," n.d.).

Vibrational treatment

An oscillatory motion forming sinusoidal and/or random waveforms at a specific amplitude and frequency can be termed as vibration, and can be positively regulated on the entire body to provide physiological benefits (Rauch 2009). Vigorous exercise or playing for about half an hour can be useful for reducing stereotypy among the children in the subject group (Kern et al. 1984). However, motivating young children (under 5 years of age) to become involved in such activities before bedtime is not practical. Therefore, a suggested alternative is to imitate such vigorous actions by applying whole body vibration for a short period. However, empirical studies of the application of such motion for the treatment of children with ASD are scarce. Only one study, conducted by Bressel et al. (2011), used a vibrational platform in a standing position for three to four sessions of 30 s reported some reduction of stereotypic behavior among young children. The benefits of such sessions as a tool for Sensory Integration Therapy have been reported independently by caregivers and parent groups (Santosg 2015). Marketers often recommend the use of such vibrational devices to reduce stress, as well as to promote restful sleep ("Vibrate Back to Health," n.d.). Clinical trials are also being conducted to understand the full effect of such therapeutic treatments (Frazier 2017).

The literature review process during this study was able to find discrete information about the efficacy of these two tools, deep pressure and vibration, when studied or used separately by researchers, caregivers, and parents to enhance sleeping habits. However, no studies combining these two unique solutions were found. In particular, no research or design effort has been paid to integrating these technologies within the potential textile platform of the sleeping environment.

Methods

Design concept

Movements during sleep were aimed to be detected via a network of pressure sensors along the back part of the sleeping bag. While nominal movements could be expected during normal sleeping conditions, frequent changes of pressure sensor data would indicate awakening. Eventually, a vibration system would be activated according to the signals received from the sensor to provide an oscillatory motion. The vibration waveform, amplitude, frequency, and duration could be manipulated to produce positive health benefits (Bressel et al. 2011). Stationary weights were intended to be mounted on the front part of the bag to impart a feeling of deep pressure touch as a semblance of a human presence to act as a calming tool (Grandin 1992). The conceptualized intelligent sleeping bag is shown in Fig. 1, and has three interactive sections: eight weight-carrying compartments, actuating motors distributed along the weight compartments and connected to networks of sensors, and a facility to withhold related hardware devices.

The design idea involved forming a network of pressure sensors along the back (down side) of the bag consisting two sewn layers of conductive fabrics separated by an insulating layer (Song et al. 2016). In a normal sleeping situation, the conductive layers are connected, forming a full circuit. However, in the event of frequent body movement, one or more sensor would become disconnected, thus sending a signal to the microcontroller, which can be placed on the closed side (opposite the zipper) in a specially protected compartment. Corresponding to the intensity of the change in sensor connectivity, the microcontroller unit would activate the connected vibrating motors that are situated between the front (upper) fabric layers of the sleeping bag. Sensor to actuator drive initiation time, duration, delay, and intensity information can be regulated ("Fading," 2015) by the coded data uploaded in the microcontroller, with the flexibility to override any new command following changed circumstances. The small, weighted bags inside the

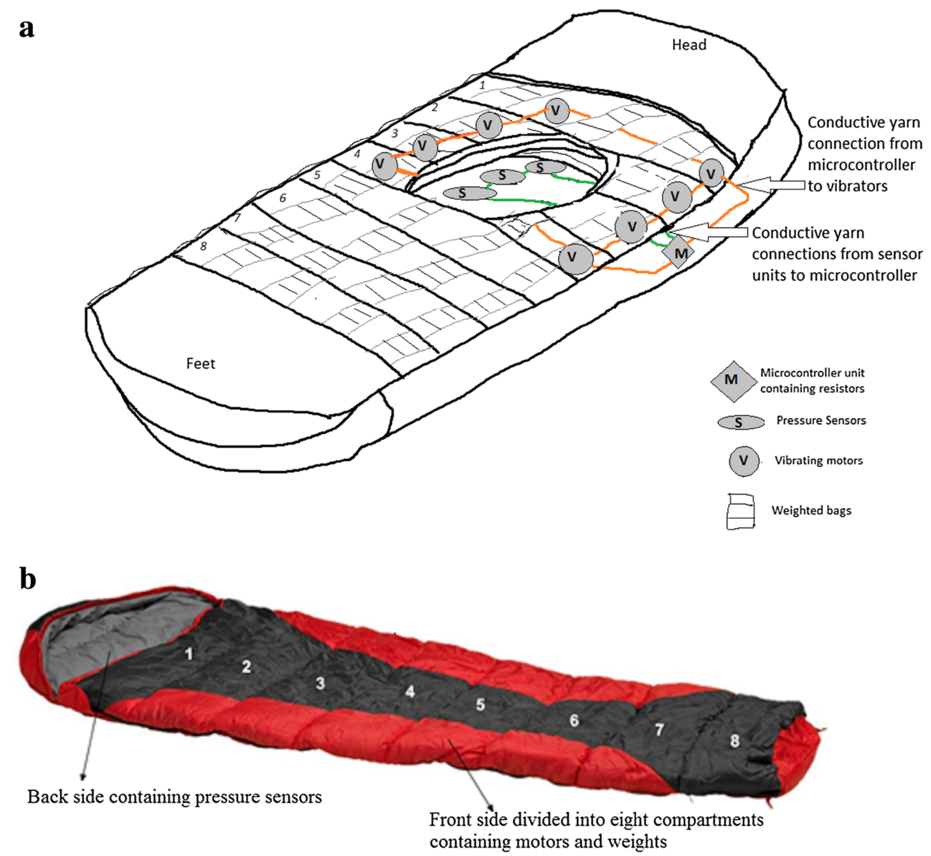


Fig. 1 Schematic (**a**) and physical (**b**) representation of the developed sleeping bag

front part provide continuous deep pressure stimuli and can be adjusted by removing any number of weighted bags according to wearer's comfort level.

Prototype construction and operation

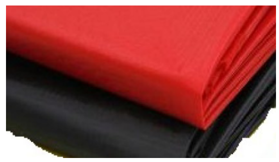
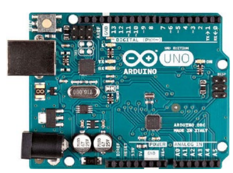
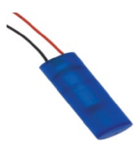
Material assembling

All the materials, devices, and software system used in this construction process are listed in Table 1 with their respective pictures and specifications.

The prototype was sewn using polyamide-based shell fabrics, ensuring lightweight and durable features. Neoprene was used as a filling and as an insulating material having adequate loft and expansion properties to ensure the wearer's comfort. Silver-coated conductive yarns were used to replace metal wiring and to produce the layers of pressure sensors. Two pieces of such conductive fabric were plain knitted and were placed on both of the insulating layers. At the pressure sensing area, three holes of 2 cm in diameter were made on the insulating neoprene piece, thus allowing the conductive fabrics to contact each other under pressure, as illustrated in Fig. 2.

Following the outline in Fig. 1, connections between the sensors and the microcontroller unit were made using conductive yarns. The controller unit was placed along the sidewall heights of the bag, ensuring minimum contact with the wearer's body in various sleeping positions. Similarly, another set of connections linked the controller unit to the

Table 1 List of materials and devices used

Material	Picture	Specification
Conductive yarn		Silver coated polyamide yarns Density 235/34 dtex Resistivity 100 Ω/m Statex GmbH, Germany
Shell fabric		100% polyamide Weight 70 g/m^2 Shelby Ltd., Finland
Filling/insulator		Neoprene 5 mm Density 170 ± 30 kg/m^3 Shelby Ltd., Finland
Weighted elements		100% polypropylene granules Kamdar Plastics, India
Microcontroller		Arduino Uno board and Arduino Software (IDE) 1.0 Arduino AG, Italy
Vibration motor		DC motor Size 8.8 mm, 3.0 V, 12,000 rpm Jinlong Machinery, USA
Resistor		220 Ω Velleman nv., Belgium

vibrating motors situated between the front parts of the fabric layers. The front part of the bag had eight evenly spaced compartments to distribute the weighted parts evenly across the body. Zipper bags filled with polypropylene granules were used as weighted components for reasons of economy and fatigue resistance. The zipper bags allow for the adjustment of the amount of granules to control the mounted load. They also provide flexibility, as they can be removed partially or completely according to the individual user's needs.

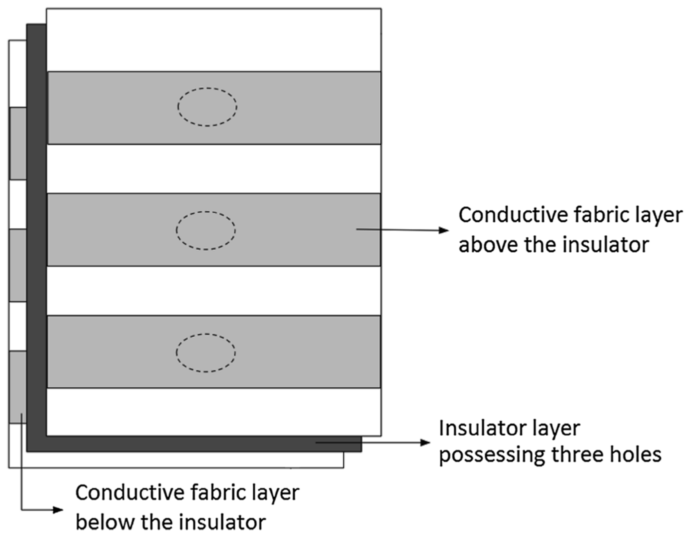


Fig. 2 Construction of three-layer pressure sensor

An open-source platform-based Arduino hardware and software system was used in this project, which includes an easy-to-use microcontroller system to read sensor inputs and thereby activate any connected actuator devices. An Arduino Uno microcontroller board was used to provide 14 digital input/output pins to be powered by dry-cell batteries. Arduino Integrated Development Environment (IDE) software, which contains a text editor for writing code for further extensions, was used.

Sensor–actuator operation

Each sensor unit operated as an on–off switch. Conductive layers of a sensor unit were initially separated by the insulating material but, under the wearer's body pressure, they were exposed to each other and formed a closed circuit. Whenever this contact was detached due to movements of the sleeping wearer, the circuit was broken (Fig. 3), and this information was sent to the microcontroller unit. By analyzing a number of movements for a given period via the set software system, the controller enabled the vibrating motors to run for two minutes at a frequency of 28 Hz (Bressel et al. 2011), providing a relaxing sensation for the wearer.

Built-in software sketches were edited to develop suitable programs for different units of this assistive sleeping bag. A "Digital Read Serial" (2015) sketch for the pressure sensor unit, a "Keyboard Message" (2015) sketch for activating the vibrating motor, and a "Fading" (2015) sketch for the desired pattern of vibration were employed. Three *pushButton* inputs were adapted for the built-in *Digital Read Serial* code for the three pressure sensors units. These were integrated with *Keyboard Message* codes, termed as *buttonState*, along with a *SimpleTimer* sketch to determine the frequency of bodily movements, and a *digitalWrite* sketch to introduce the duration of vibration.

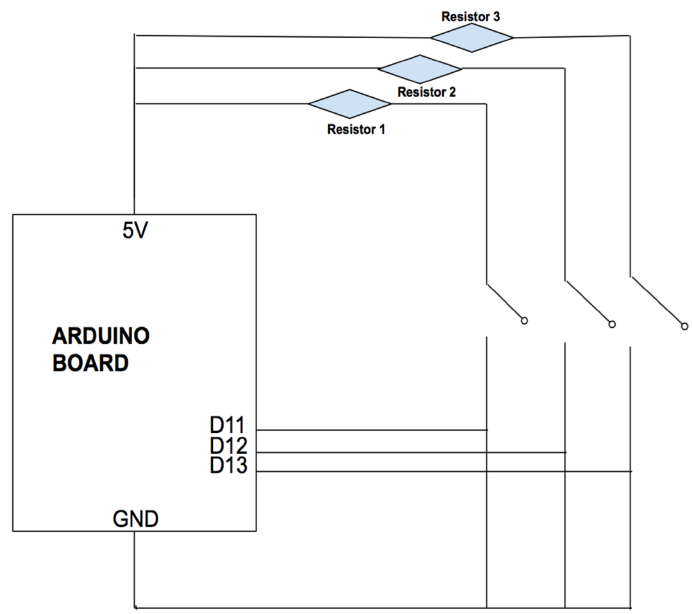


Fig. 3 Parallel circuit setup of pressure sensor unit

Prototype validation

Human subjects and ratings

The prototype system was tested on two female and one male student volunteers who had no history related to ASD, who were between 19–25 years of age, and who weighed in the range of 48–73 kg. They subjectively rated the efficacy of deep pressure touch and vibration to exert a relaxing and soothing sensation (Grandin 1984; Krauss 1987) according to a five-grade scale (Excellent > Very Good > Good > Fair > Poor).

Testing and analysis procedure

To evaluate the effect of the time of day of the sleeping bag on its efficiency level, each responder was subjected to experience the actuation in different sessions: early morning, afternoon, and late in the evening, reflecting the sleeping patterns of children with ASD (Kotagal and Broomall 2012), and on 3 separate days to provide the opportunity for a fair assessment. The front part of the bag was filled with weights corresponding to 8% of the responder's body weight based on the recommendations of occupational therapists ("What is the Right Sized," n.d.). Each responder was subjected to ten vibration intervals during a session, leading to 90 observations for three responders in total. The duration of each observation was approximately 5 min (movement sensing and vibrating), providing sufficient time to evaluate the sensation. A break of 2–3 min was allowed between consecutive observations to maintain the usual bodily states of the responders.

Results and discussion

The primary aim of this design validation was to understand the vibration impacts under the mounted weights in the upper compartments. The brief evaluation process showed that the impact of vibration on the soothing sensation was rated by the responders to be "very good" about 40% of the time and "good" for about 20–30% of the time during the entire test period. Proving the effectiveness of the developed system, the response "excellent" was mentioned about 20% of the time by two responders. However, the third responder mentioned it only 3% of the time, showing variation in the highest level of efficiency, which could be dependent on the personal perception at an extreme level for any particular user (Parsons and Griffin 1988).

By comparing the ratings of different daytime sessions to understand any variation in the sensations felt for the same amount of vibration exerted, it was found that about 40% of the responses were "Excellent to Very good" during evening sessions compared to about 30% during the other two sessions. It shows the acceptable vibration effectiveness of the assistive sleeping bag throughout the day. However, an increase in the comfort rating during the evening may have been related to the tiredness of the responders at the end of the day (Kubo et al. 2001).

The combined results of all 90 observations show that about 75% of the vibration responses were rated at the top three levels of the scale ("Excellent", "Very good", and/or "Good"), supporting the potential of this assistive sleeping bag for the intended purpose, which is also supported by no responder reporting a "Poor" rating.

Apart from the sensor–actuator functioning, an important aspect covered in this design project was the replacement of the metal wiring with conductive yarns corresponding to the product's stipulation to accommodate recurrent bending movements, heavy load-bearing capacity, and greater comfort (Meoli and May-Plumlee 2002). Due to their effectiveness and versatility, silver-coated conductive yarns are being used in many other smart textile and wearable technologies, as they not only provide a flexible conductive solution, but also have the anti-static, anti-microbial, and biocompatibility properties of silver, as well as excellent resistance to sterilization and long-term durability (Pollini et al. 2009).

Conclusion

A wearable, therapeutic device possessing smart textile-based sensors and actuators to treat sleeping disorders among autistic children was designed successfully in this study. A prototype of the designed sleeping bag, integrated with a pressure sensor, a few weighted compartments, and a vibration actuator was built to detect the awakening stage of the user, and to provide soothing vibratory motions in the form of wearable technology while maintaining the required comfort level for everyday use.

The constructive use of conductive yarns and easily accessible open-source based hardware and software systems in such facilities was demonstrated favorably. In addition to treating sleeping disorders, such a solution is expected to improve the quality of the daily lives of the children and their parents. Overall, the study was able to design an assistive tool to treat children with sleeping disorders by sensing the point of waking state and then actuating a vibrational calming stimulus in the form of a smart textile-based sleeping bag with the scope for improvement with regard to the combined actuation effect in more customized applications. The main limitation of the study remains conducting clinical trials for children with ASD, in addition to the opportunity for alteration to the design and evaluation of the interdependency between weight and the vibrational effect.

The major contribution of the study is the demonstration of how a traditional textile-based product can be improved by design adaptation for wearable technology. Thus, reflecting on the future of textiles and fashion, this study sought to encourage the integration of readily available electronic and computing devices within common textile platforms to administer advanced solutions. More specifically, the concept and design development, the material integration approach, and the validation data presented in this pilot study can be used for commercial development and clinical trials of assistive sleeping bags for children with ASD.

Limitations and implications for future research

Fully equipped clinical trials involving children with ASD are necessary to evaluate the efficiency of the developed prototype for practical uses. This was not possible during this project due to a lack of resources, and can thus be listed as the main limitation of the study.

The current prototype design involves a limited number of sensors, and actuator units are set only around the upper part of the wearer's body, which can be expanded to the area near the feet. However, studies concerning the relationship of the movements of different body parts to the awakening state need to be considered in such designs. Increasing the number of sensor units would require a complex network of wiring that would necessitate a more efficient design for the entire bag. In addition, a data-storing component could be added to the mounting hardware to analyze the sleep pattern information with the help of medical professionals.

It is of immense importance to understand any effect of the mounted weights on the level of vibration exerted to ensure a combined soothing sensation. Therefore, at a later point in this study, the front compartments of the bag were filled with 5 and 15% of the responder's body weight (instead of the recommended 8%) to examine such correlations. However, the responses received were too diverse to draw any conclusions; thus, there is a need for further research on such modifications because as the weight requirement may vary significantly among the individual children under concern that may benefit from the product.

In addition to the mounted weights, variations in the vibrational frequency can affect the level of sensation required for sleep, and also need to be studied more extensively. The assembly of the developed assistive sleeping bag has great potential for commercialization due to the features of easy customization depending on the precise requirements of the children receiving treatment following the proposed developments.

Authors' contributions

TTB, RSI, and SH have done the literature study, concept and prototype development, data acquisition and analysis, and manuscript drafting. LB contributed in developing the concepts, designing the experiments and supervising the project. TTB prepared the manuscript submissions after critical revisions by all the authors. All authors read and approved the final manuscript.

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Ethics approval and consent to participate
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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