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REVIEW

Review of assistive devices for the prevention of pressure ulcers: an engineering perspective

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ABSTRACT

Purpose: Pressure ulcers (PUs) are prevalent among immobile bed or wheelchair-reliant individuals who experience prolonged sedentary positions. Pressure relief and frequent repositioning of body posture help to mitigate complications associated with PUs. Adherence with regular repositioning is difficult to maintain due to nursing labour shortages or constraints of in-home caregivers. Manual repositioning, transferring, and lifting of immobile patients are physically demanding tasks for caregivers. This review aimed to explore and categorize these devices, discuss the significant technical challenges that need addressing, and identify potential design opportunities.

Materials and Methods: In this review, a literature search was conducted using PubMED, Science Direct, Google Scholar and IEEE Xplore databases including studies from 1995 until Feb 2023 with keywords such as pressure ulcer, assistive device, pressure relief, repositioning, transfer, etc. Both commercial and research-level devices were included in the search.

Results: 142 devices or technologies were identified and classified into four main categories that were further subcategorized. Within each category, the devices were investigated in terms of their mechanical design, actuation methods, control strategies, sensing technologies, and level of autonomy. Limitations of current technologies are design complexity, lack of patient comfort, and a lack of autonomy requiring caregivers frequent intervention.

Conclusions: Several devices have been developed to help with prevention and mitigation of PUs. There remain challenges that hinder the widespread accessibility and use of current technologies. Advancements in assistive technologies for pressure ulcer mitigation could lie at the intersection of robotics, sensors, perception, user-centered design, and autonomous systems.

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➤ IMPLICATIONS FOR REHABILITATION

- Future advancements in assistive technologies for pressure ulcer mitigation could lie at the intersection of robotics, sensors, perception, user-centered design, and autonomous systems.
- Most existing technologies for prevention of pressure ulcers are focused on the mechanical advantage rather than user's needs and preferences. Future designers, engineers, and product developers must be educated to conduct user needs studies concurrently with the development of technology to design the devices based on the user's needs to ensure a balanced design outcome.

Introduction

A pressure injury, also known as a pressure ulcer (PU), bedsore, pressure sore, or decubitus ulcer, is defined as a localized damage to the skin and/or underlying tissue as a result of intense and/or prolonged exposure to sustained deformations by compressive and/or shear loading [1]. PUs mostly occur in individuals who have limited ability to move part or all of the body, including patients with a loss of mobility due to spinal cord injury, frailty from aging, obesity, stroke, and severe injury due to an accident [2]. PUs can give rise to several complications including negative physical, psychological, and social consequences affecting health and well-being of individuals [1,3]. These include increased morbidity and mortality, pain, discomfort, depression, lowered autonomy and security, and impaired social functioning [4]. In the United States, in the period between 2000 to 2012, the cost of pressure injury care was estimated to approach \$11.6 billion annually with an individual patient care cost ranging between \$500 and \$152,000 depending on the wound severity, hospitalization duration, clinical settings, etc. [1].

Mechanical loading (i.e., pressure and/or shear forces) causes twisting and blocking of the microcirculation needed for the exchange of the oxygen, carbon dioxide, nutrients, water, and waste products. As a result, the localized ischemia changes adversely affect tissue viability, which is the primary cause of PUs [5]. Externally applied pressure decreases the tissue viability. Shear forces can twist and close the blood vessels in the

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microcirculation, cause delamination of tissue layers, and rupture cells due to high internal stresses and strains, thus causing direct cell death. While pressure has the highest impact on the deeper layers of the tissue around bony parts, shear is known to have the most effect on the superficial layers of the skin [5].

A significant body of the literature has also focused on investigating the influence of body posture on the interface pressure between the body and the support surface [6]. Some of these studies have experimentally measured some metrics such as the peak interface pressure, normal and shear interface forces, the movement of the center of pressure, etc. as an indication of PU risk factor while changing the posture. Others have proposed using computational models to capture the force exchange between the body and the support surface for different postures [6]. Geffen et al. [7] developed an experimental adjustable simulator chair to investigate the effect of sagittal postural adjustments (i.e., pelvis rotation and chair recline) on seat reaction load. Their study concluded that a combination of independent pelvis rotation and seat inclination can regulate the buttock net shear and sacral interface pressure. Yoshikawa et al. [8] evaluated the interface pressure between the sacrum and greater trochanter area in bedridden patients in the supine, 90° lateral position, as well as 30° and 40° laterally inclined positions with external rotation or neutral positioning of the hip joint. The study results indicated that the hip-joint rotation did affect the interface pressure, likely due to the increased distance between the greater trochanter and the sacrum caused by neutral position of the hip joint. Källman et al. [9] also showed that the lying posture influences the tissue blood flow over the bony parts in different ways in older adult inpatients. Defloor [10,11], a pioneer researcher in the field of PUs, also experimentally investigated the effect of four different supine positions, three lateral positions, and two prone positions. His experiments showed that the 30° tilted side lying position and the prone position resulted in the lowest interface pressure whereas the 90° side lying position resulted in high pressures and must be avoided. This difference is due to the contact area between the body and the support surface where in the 90° side lying, the body rests only on the trochanter near the pelvis and the body weight is distributed in a small tissue mass. However, in the 30° side lying, the contact area is larger, thus the pressure is low. Thus, the results of all these studies demonstrate that posture change does influence the interface pressure exerted on the body, therefore, there's a variable risk of PU depending on the posture.

Therefore, to alleviate the development of PUs, immobile patients need pressure relief and frequent repositioning in their body posture. Pressures greater than 32 mmHg (capillary filling pressure) and exceeding 2 h at the heels and sacrum of patients may cause necrosis [12,13] Wheelchair users are encouraged to perform pressure-relieving exercises every 15–20 min [14]. Patients in bed are expected to be repositioned to a different body side every two hours [15], and a tilt of 30° is considered sufficient for offloading [16]. Adherence with this frequent manual repositioning is difficult to maintain, generally due to nursing labor shortages in healthcare institutions or commitments of in-home family caregivers [17]. As a result, only about 66% of patients receive this treatment regularly. Manual repositioning, transferring, and lifting patients are physically strenuous tasks. They can result in skin abrasions or patient falling, and cause musculoskeletal disorders for the caregiver [18].

To reduce the development of pressure ulcers and assist caregivers with repositioning and transferring patients, researchers and companies have proposed and developed a variety of assistive devices. These devices provide assistance with pressure relief, repositioning, transferring, or a combination of these strategies (Figure 1). Pressure-relieving devices reduce the pressure magnitude or duration such that the pressure between the body and the support surface does not exceed 32 mmHg. Repositioning devices can roll the patient from one side to the other side. Transfer devices help caregivers move patients in and out of beds or wheelchairs. Combined strategies merge pressure relief, patient repositioning, and/or patient transfer capabilities. Design complexity, patient discomfort, and lack of device autonomy requiring caregivers to intervene frequently are major drawbacks observed in these devices. There is no combined solution that can autonomously and simultaneously relieve pressure, reposition, and transfer the patient, despite recent advancements in robotics, sensing technologies, perception, user-centered design, and autonomous systems. Thus, future advancements in assistive technologies for pressure ulcer relief could lie at the intersection of these fields. To the best of authors' knowledge, this is the first review paper that explores the existing technology for the prevention and mitigation of pressure ulcers from a design and engineering perspective. The objectives of this review paper were to (1) identify and classify the state-of-the-art assistive technologies for PU prevention, (2) investigate these technologies in terms of their mechanical design, control strategies, sensing technologies, actuation methods, and device autonomy, (3) discuss the significant technical challenges that need addressing, and (4) identify potential design opportunities for future innovations.

Review methodology

Our review surveyed published research papers, US patents, and commercial devices on pressure-relieving, patient repositioning, patient transfer, and combined devices as well as sensing technologies for pressure ulcer detection in four electronic databases including PubMED, Science Direct, Google Scholar, and IEEE Explore with different combinations of these keywords: pressure ulcer, pressure injury, bedsore, pressure sore, decubitus, prevention, treatment, mitigation, patient, bedridden, immobile, wheelchair, bed, wheelchair user, anti-decubitus, pressure relief, reposition, roll, turn, side, transfer, move, device, apparatus, support surface, pressure, sensing, sensor, technology, assistive, autonomy, automatic, autonomous, posture detection. These keywords were specifically used to: 1) include all possible references on the topic of pressure ulcers (e.g., pressure ulcer, pressure injury, bedsore, pressure sore, decubitus), 2) include all possible four categories of assistive devices and technologies for the prevention and mitigation of PUs that were introduced in the introduction section (e.g., prevention, treatment, mitigation, wheelchair, bed, anti-decubitus, pressure relief, reposition, roll, turn, side, transfer, move, device, apparatus, support surface, pressure, sensing, sensor, technology, assistive, autonomy, automatic, autonomous, posture detection), 3) include all devices/technologies for immobile patients, bedridden individuals as well as wheelchair users as the target population of the study (e.g., patient, bedridden, immobile, wheelchair user).Review references related to the topic that were not found with the search criteria but found from references in other studies were also included. Additionally, since the goal of this study was to include both commercial and research-level devices, some of the commercial devices not listed in the published literature were explored through a simple online search in Google. All scholarly studies and commercial product catalogues and websites were written in English except for [19] which was in Japanese but was translated to English using Google Translate. Studies were considered from 1995 until Feb 2023 to provide a comprehensive study of the literature on the devices in the past three decades. In total, 142 references were selected where 26 were for pressure-relieving, 23

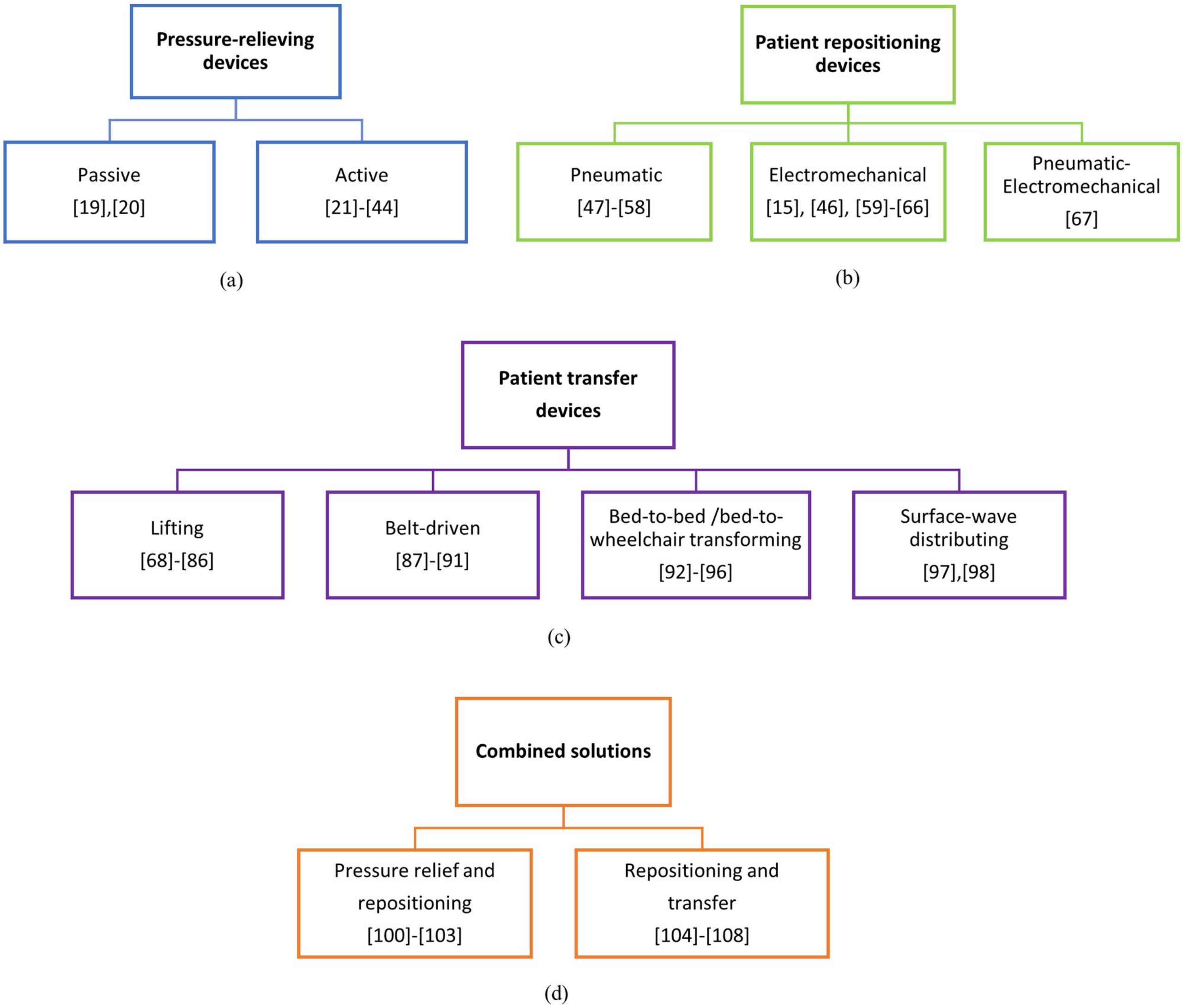

Figure 1. Proposed classification categories of assistive devices for prevention of pressure ulcers among immobile individuals. Relevant references are cited within square brackets.

for patient repositioning, 32 for patient transfer, 9 for combined solutions, and 52 for pressure ulcer detection sensing technologies as well as autonomy of the devices.

There exist a few research papers and reviews in the literature which have investigated the existing pressure ulcer mitigation technologies from a clinical perspective such as randomized control trials that assess the effect of support surfaces for pressure ulcer prevention. These studies were excluded from our search findings because the focus of this study was to explore the existing literature from an engineering and not a clinical perspective. Additionally, a large body of the literature has been dedicated to the clinical publications, and to the best of our knowledge, no similar prior work has been published so far that have studied the devices from an engineering viewpoint. This review explores these technologies from an engineering perspective with a focus on the mechanical design, controls architecture, actuation methods, and sensing technologies.

Pressure-Relieving devices

Pressure-relieving devices were classified into two main categories: A) passive, and B) active devices, based on the strategy that they employ to change the pressure distribution under the body. Passive devices reduce the 'magnitude' of the peak pressure whereas active devices reduce the 'duration' of the applied pressure. Below, some passive and active devices that are commercially available or reported in the literature are described and categorized.

(A) Passive devices

Passive devices, also known as reactive, static pressure-reducing, or constant low-pressure devices, include foam, gel-filled, fiber-filled, air-filled, water-filled, and bead-filled mattresses, overlays, and seat cushions. They increase the contact area by conforming to the patient's body shape resulting in a greater immersion of the person into the device and redistributing the pressure [2]. Most passive devices are commercial (e.g., [20,21]) and there are very few recent research papers that have focused on passive devices. This review paper focuses on the active devices which are described in the next subsection.

(B) Active devices

Active devices which are also known as dynamic pressure-reducing or alternating support surfaces employ pneumatic and electromechanical actuation strategies to offload pressure, which are further explained in the following.

The majority of active devices use pneumatic pressure modulation systems to reduce the pressure (Figure 2, Table 1). These devices include bed mattresses and seat cushions that are made of individual soft air bladders that inflate and deflate periodically to modulate the pressure. Commercial bed mattresses are predominantly based on a series of 18–20 large air tubes aligned transversely to the body [22,43–45] (Figure 2(a)). Some products cycle through predefined pressures [15,22], while others monitor and distribute pressure across large regions of the body [43]. Similarly in the academic literature, Moon et al. [28] developed an air mattress consisting of 18 air tubes where the mattress was divided into four main sections including the head, trunk, hip, and legs and the pressure in each section was controlled to be less than 32 mmHg. However, it was unclear if it was possible to select specific sites (e.g., not across large body areas) to offload the pressure. To address the lack of site specificity due to large air bladders, Takashima et al. [23] proposed a bed mattress made from stacking two arrays of 49 soft urethane air bladders with the intent to deflate each air bladder to different heights based on data from a custom capacitive pressure sensor mat placed on top of the mattress (Figure 2(b)). Similar work was done by Misaki et al. [29] from the same research group where they proposed an air mattress consisting of individual air bladders and smart rubber sensors which could change its surface automatically to fit the patient's body contour. A new patented mattress design was proposed by Alwasel et al. [30,31] which included a cavity in the middle, mainly under the human body torso and hip where three different removable cube designs that could be either integrated or removed from the cavity to locally change the pressure distribution underneath the body. Nair et al. [32] proposed a smart air mattress divided into different zones whose pressure could be independently controlled using force sensing resistive pressure sensors, and automatically adjust the pressure level and change patient's posture on the mattress. Lee et al. [33] proposed a pneumatic mattress composed of individual longitudinally arranged air cells, with embedded non-contact Time-of-Flight optical sensors at the bottom, which could indirectly measure the body pressure on the mattress by sensing the changes in the bladder's height and perform an active control to modulate the pressure. Similarly, Carrigan et al. [24] (Figure 2(c)), Nakagami et al. [34], Fadil et al. [35] and Arias et al. [36] developed seat cushions which could offload pressure from specific sites under the body. In a similar work, Mannella et al. [37] proposed the conceptual design and control of an active pressure-relieving cushion in simulation with the intent to perform site-specific pressure relieving by identifying high and low-risk PU development regions. Chenu et al. [38] also proposed a fully wireless, customizable, and washable wheelchair cushion mat, called TexiCare, made of a piezoresistive textile for measuring pressures, with tactile-visual alert feedback to the user in the case of identifying high pressures areas. In another design, Fiedler et al. [25] developed an adaptive intelligent bed surface technology called IANSiS made of an array of 5724 small plastic pins aligned in a hexagonal pattern and held in place in a layer of PVC (polyvinyl chloride) with an underlying array of air bladders (Figure 2(d)). The system continuously and locally monitored the patient's skin condition and inflated and deflated the air

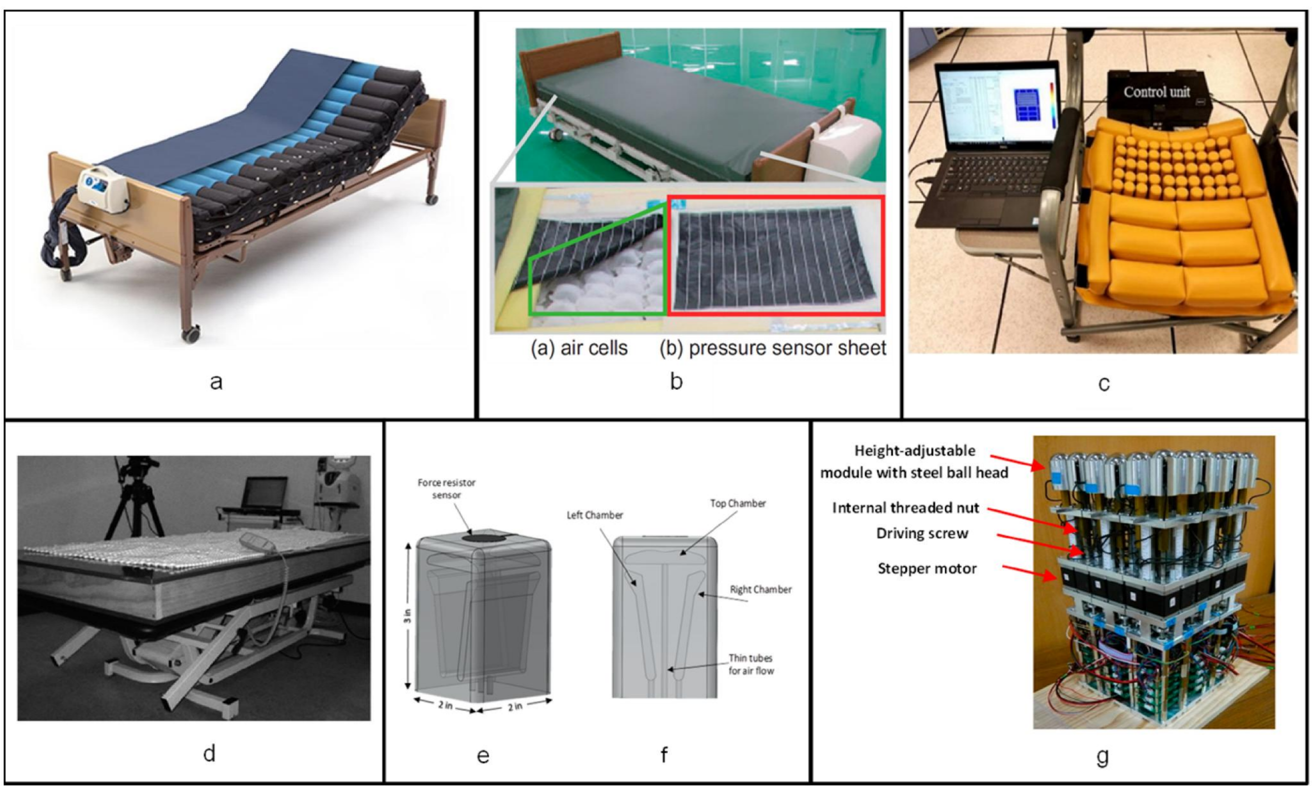

Figure 2. Active pressure-relieving devices. (a) Commercially-available Invacare Corporation bed mattress [22], (b) bed mattress proposed by Takashima et al. [23], (c) automated pressure-mapping and modulating seat cushion by Carrigan et al. [24], (d) IANSiS bed prototype by Fiedler et al. [25] (e) isometric view and (f) front view of the proposed pressure-relieving seat cushion using dome-shaped silicon rubber actuators consisting of three separate pneumatic chambers developed by Raeisinezhad et al. [26], and (g) proposed pressure-relieving seat cushion using modularized height-adjustable system adapted from Yu et al. [27].

Table 1. Summary of active pressure-relieving devices.

Reference	Device name	Device description	Sensors used
Moon et al. [28]	Not specified	Air mattress made from 18 pillow-shaped air bladders divided into four parts for head, trunk, hip, and leg. Pressure in each part $<$ 32 mmHg.	Pressure sensors
Takashima et al. [23]	Not specified	Air mattress consisting of 49 air bladders made from 2-stack arrays with overlying pressure sensor mat.	Capacitive pressure sensors
Misaki et al. [29]	Not Specified	Air mattress consisting of a 2-stack array of 6×10 air bladders which could change its surface automatically to fit the patient's body contour.	Capacitive pressure sensors
Alwasel et al. [30], Alsadun [31]	Not Specified	Polyurethane foam mattress including a cavity in the middle, mainly under the human body torso and hip with three different types of removable cube designs for local pressure change.	Not Specified
Nair et al. [32]	Not specified	Air mattress with independently controlled support zones on each side.	Force sensing resistive (FSR) sensors
Lee et al. [33]	Not Specified	Air mattress composed of individual longitudinally arranged cylindrical air cells.	Time-of-Flight optical sensors.
Carrigan et al. [24]	Not specified	Seat cushion made from array of 62 cylindrical and rectangular air bladders.	Pressure sensors
Nakagami et al. [34]	Not specified	Seat cushion made from array of 35 small and 4 large air bladders with automatic self-regulating alternating pressure system.	Pressure sensors Displacement sensors
Fadil et al. [35]	Not specified	Seat cushion made from an array of 7×7 air-cell zoned seated area.	Not specified
Arias et al. [36]	Not specified	Seat cushion made from an array of 12 air bladders divided into two zones for pressure relief.	Pressure sensors
Mannella et al. [37]	Not specified	Conceptual design of a seat cushion composed of four pressure areas at different risk levels with integrated cylindrical air cells.	Not specified as the study is about the conceptual design and simulation of the cushion prototype
Chenu et al. [38]	TexiCare	A wireless customizable and washable three-layer textile map able to measure pressure and provide tactile visual alert to the user if the pressure exceeds a certain amount.	An array of 32×32 piezo-resistive sensors
Fiedler et al. [25]	IANSiS (Adaptive Intelligent Bed Surface Technology)	Hexagonal array of 5724 small plastic pins held in place in layer of PVC material with underlying assembly of $40 \times 40\,\text{cm}^2$ air bladders each interfacing with 15 pins. Air bladders inflate and deflate to raise and lower pins to conform to body shape.	Pressure sensors Temperature sensors Moisture sensors Shear sensors
Li et al. [39]	Not specified	Method for fabrication of a foam seat cushion customized to the user's buttocks shape by mapping the pressure distribution to the cushion carving depth.	Pressure sensor mat
Raeisinezhad et al. [26]	IntelliPad	Proposed seat cushion design that would consist of array of 9×9 dome-shaped silicon rubber actuators (overall size of cushion: $410 \times 460\,\text{mm}^2$). Each actuator having 3 chambers independently pressurized and controlled horizontally and vertically to redistribute normal and shear forces.	Force sensitive resistor
Elfehri et al. [40]	Not specified	Air mattress made from array of 10×20 air cells with embedded pressure sensors.	Pressure sensors
Yu et al. [27]	Not specified	Seat cushion made from array of 6×6 height-adjustable modules whose heights could be adjusted *via* stepper motors and customized to buttocks shape in real-time.	Force sensors Position sensors
Cernasov et al. [41]	Not specified	Array of length-adjustable coil springs with overlying paddings for reducing pressure *via* different proposed mechanisms such as cables, flywheels and belts.	Position sensors Pressure sensors Temperature sensors
Seon et al. [42]	Not specified	Robotic bed consisting of multiple independently controlled segments, each driven by a four-bar mechanism and brushless DC motor for local pressure distribution change.	An array of force sensing resistor (FSR) sensors

bladders to raise and lower the pins to conform to the user's body shape. Li et al. [39] also proposed a method for the fabrication of a custom-contour seat cushion where the interface pressure distribution under buttocks was converted into the carving depth of cushion to modulate the pressure. However, all of these solutions would only reduce the normal forces applied to the user's body and not shear forces. Recently, Raeisinezhad et al. [26] conceptualized a seat cushion, called IntelliPad, constructed from an array of dome-shaped silicon rubber actuators each having three chambers (Figure 2(e,f)). Each individual actuator could measure the contact forces and was independently pressurized both in the horizontal and vertical directions. This feature provided the ability to redistribute normal and shear forces on the user's skin. However, the authors conducted some experiments to show the force distributing capability of only a simplified version of the cushion (i.e., only three adjacent actuators). Future research is needed for the fabrication and clinical validation of a complete cushion prototype as well as simultaneous redistribution of normal and shear loads.

Other researchers have focused on electromechanical pressure modulation systems where height-adjustable actuators are electromechanically actuated to actively change the support surface shape to conform to the body's contours. Elfehri et al. [40] developed a foam mattress consisting of an array of smaller cells where

Table 2. Summary of pneumatic repositioning devices.

Reference	Device name	Device description	Sensors used	Tilt angle range (degrees)
Hasty et al. [49]	Not specified	Air mattress made from two longitudinal rolling chambers for rolling over the patient through inflation of one chamber and deflation of the other chamber.	Not specified	Not specified
Bodine et al. [50]	Not specified	Array of 8 side-by-side cylindrical longitudinal air chambers which inflated and deflated to turn the patient.	Not specified	0–40
Prius Co. [51]	Rhythm Turn	Commercial pneumatic bed mattress made from a series of large air tubes aligned transversely to the body that could turn the patient by inflation of the air bladders in one side.	Not specified	20 and 40
Collymore, 2001 [52]	Not specified	Two sets of stacked wedge-shaped air bladders in the right and left sides that could rollover the patient to one side through sending air to one of the stacks.	Not specified	Not specified
Blevins and Brook, 2009 [53]	Not specified	A pair of air chambers separated by a hinge line, each consisting of parallel rectangular air bladders extending longitudinally along the length of the chamber that formed a wedge structure while inflated and could rotate a patient.	Not specified	0–90
Haas et al. [54]	Not specified	Turning device secured under a conventional air mattress and consisting of two arrays of butterfly-shaped stacked air bladders inflated and deflated to turn the patient.	Not specified	0–90
Mangar Group [55]	Ekamove	Automated, sensor-controlled commercial dual air chamber placed under a support surface to turn the patients.	Not specified	0–30
Galer et al. [56]	Not specified	Two assemblies of stacked air bladders in two sides under a mattress that inflated individually to turn the patient.	Force sensors Angular position sensors	Not specified
Chugo et al. [57]	Not specified	Four sets of square stacked air bladders under a wheelchair cushion that pressurized and depressurized to assist the patient with side or forward movements.	Pressure sensor sheet consisting of 360 pressure sensors	Not specified
Frontier Medical Group [58]	Toto lateral turning system	Two arrays of air bladders in the right and left sides with three overlying rigid sheets, each folded longitudinally along two lines defining two main regions under the body. The bladders inflated and pushed against the sheets to roll the patient over.	Not specified	Not specified
Zhang et al. [59]	Not specified	Foam mattress divided into two parts on the left and right sides, with built-in pneumatic air bags underneath for patient lateral turn.	Gas pressure sensor Infrared temperature sensor	25
Fraiszudeen et al. [60]	Sit-to-stand trainer seat	A soft sit-to-stand device composed of two sets of pneumatic bellow-type actuators that transitioned between a fully deflated configuration to a semi-standing position to help individuals transition from a sitting posture to a standing position.	Inertial measurement unit (IMU)	45
Hsu et al. [61]	Not specified	Adjustable seat platform with an integrated four-axis Stewart platform capable of heaving, pitching, and swaying to provide seat elevation, tilt-in-space, and sideways movement functions. Seat also equipped with soft pressure-sensing pads to provide pressure relief.	Optical sensor Pressure sensor pads	22 (CW) and 15 (CCW)

each was independently and vertically actuated using a motorized system for local pressure distribution change under different body parts. Yu et al. [27] developed a modularized seating system including support elements with steel ball heads and embedded load cells that could be customized to the buttocks shape in real-time (Figure 2(g)). Similarly, Cernasov et al. [41] designed a support surface consisting of an array of programmable supports whose length could be adjusted *via* different mechanisms such as a belt and flywheel system to reduce the pressure on the patient's skin. Similarly, Seon et al. [42] proposed a novel robotic bed to prevent the formation of pressure sores, consisting of multiple independently controlled segments, driven by a four-bar mechanism and a brushless DC motor to change the pressure distribution under the body and prevent the formation of PUs. This design concept is similar to the work by Yousefi et al. [46] which will be further discussed under the repositioning devices.

Repositioning devices

Repositioning involves rolling the patient to a side and supporting the body at an incline to prevent the patient from lying on ulcerated locations. Generally, repositioning is done with passive

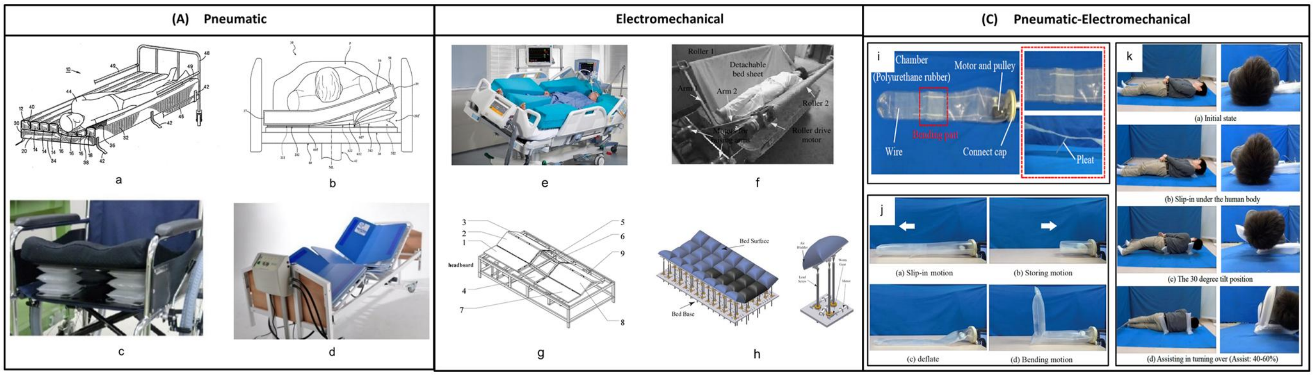

Figure 3. Repositioning devices. (a) Bed mattress proposed by Bodine et al. [50], (b) turning apparatus by Galer et al. [56] where multiple air bladders were stacked to increase patient's tilting angle, (c) depressurization assistance system by Chugo et al. [57], (d) commercially-available Toto Lateral Turning System [58], (e) commercially-available Linet Multicare bed [48], (f) Marionette Bed by [15,62], (g) robotic nursing bed by Tan et al. [63], (h) smart bed platform by [46,64] (i) components of the repositioning device based on a soft pneumatic slip-in manipulator by Nakamura and Tsukagoshi [65], (j) overview of manipulator motions, and (k) steps to turn the patient over.

devices such as high-density foam wedges or pillows supporting the patient to maintain the inclined position. Commercial repositioning devices range from simple manual slings [47] to motorized tilting hospital beds [48]. A few research studies and product developers have explored alternative ways to perform active repositioning that were classified into three main categories based on the actuation method that they use to turn the patient: A) pneumatic, B) electromechanical, and C) pneumatic-electromechanical.

(A) Pneumatic devices

These devices use pneumatic actuation strategies to turn the patient (Table 2, Figure 3(a–d)). They include mattresses and seat cushions consisting of an array of air bladders that can selectively be inflated and deflated to turn the individual [49–60] (Figure 3(a)). To increase the tilt angle, some designs have stacks of multiple air bladders. When the air bladders in one side are inflated, they form a wedge-shaped structure, thus, repositioning the individual to one side [52–57] (Figure 3(b)). An example of this category is Chugo et al.'s work [57] where they developed a depressurization assistance system for wheelchair users who do not have enough physical strength to move themselves forward or to the side when performing pressure-relieving exercises (Figure 3(c)). The system consisted of four sets of stacked air bladders in the four corners under an aluminum base below a wheelchair cushion. The device detected the changes in the body's center of pressure using a pressure sensor sheet and used an algorithm to identify if the patient was trying to perform a lateral tilt or forward inclination. The air bladders then inflated to incline toward the side they were trying to move. Another example is the ToTo Lateral Turning System [58] which consists of three rigid panels under the torso, hip, and legs. The air bladders inflate and push against the rigid sheets, hence, bending the sheets along their folding lines and turning the patient. In a similar work, Fraiszudeen et al. [60] proposed a soft sit-to-stand device which was composed of two sets of pneumatic bellow-type actuators. Each set of stacked bladders could transition between a fully deflated configuration (i.e., horizon) to 45° (i.e., the semi-standing position) to help individuals to transition from a sitting posture to a standing position.

(B) Electromechanical devices

These devices employ electromechanical actuation strategies to turn the patient (Figure 3(e–h), Table 3). Commercial devices include motorized tilting hospital beds such as Multicare Bed [48], which can automatically rotate around the longitudinal axis of the bed (Figure 3(e)). However, they are expensive and bulky. Among research studies, Hsu et al. [61] proposed an adjustable seat platform where a four-axis Stewart platform was used which was capable of heaving, pitching, and swaying to provide seat elevation, tilt-in-space, and sideways movement functions. The seat was also equipped with soft pressure-sensing pads to provide pressure management by adjusting the seat mechanism once continuous and concentrated pressure was detected. In another study, a bed prototype, called Marionette Bed, was designed, and built with a bed sheet secured into overhead rollers, where the patient was supported as in a hammock (Figure 3(f)). Servo motors retracted one side of the sheet so that the patient was gently inclined while friction was sufficient to prevent slipping. A closed-loop feedback control algorithm was implemented to control patient's position and orientation under repositioning [62]. However, one of the major drawbacks of this design was that use of bed sheets might still affect ulcer locations (especially for patients who have a severe pressure ulcer condition) which may cause discomfort for the patient. Tan et al. [63] designed a voice-controlled robotic bed with 9 panels that sat atop the frame, three each under the legs, hips, and head and back (Figure 3(g)). Two DC motors on either side of the bed turned the patient and a third motor at the center could raise the patient's back. In a similar work, Andhare et al. [66] proposed a bed where a similar lateral turn idea as Tan et al.'s work [63] with the addition of backrest adjustment functionality. A bed-chair mechanical design and a method for automatic lateral turn of the human body in simulation was also proposed by Ezzet et al. [67]. Similarly, the commercially-available Freedom Bed [68] operates mechanically through bending three separate platforms that are hinged together. The platforms smoothly bend and form a wing-shaped structure, and the patient is repositioned to one side. In another design, a smart bed platform made of smaller tiled units was proposed where each unit could be independently actuated with three DOFs *via* a mechanical actuation mechanism (Figure 3(h)). A machine learning algorithm was implemented to identify a patient's risk of developing a pressure ulcer based on pressure, temperature, and moisture sensors. Mechanical actuators were controlled to periodically adjust the bed surface profile to redistribute pressure over the entire body. A single unit prototype was manufactured and open-loop controlled as a proof-of-concept [46,64].

(C) Pneumatic-electromechanical devices

One study used a combination of electromechanical and pneumatic actuation methods to roll the patient over (Figure 3(i–k), Table 4). Nakamura and Tsukagoshi [65] proposed a soft

Table 3. Summary of electromechanical repositioning devices.

Reference	Device name	Device description	Sensors used	Tilt angle range (degrees)
Linet Co. [48]	Linet Multicare Bed	Commercial bed that provided continuous rotational lateral therapy about the longitudinal axis of the bed to turn the patient.	Not specified	0–30
Basmajian and Asada [62] and Roy et al. [15]	Marionette Bed	Hammock-shaped bed consisting of a bedsheet secured to two rollers that could gently turn the patient by winding and unwinding the bedsheet around the rollers.	IMU Encoder	0–180
Tan et al. [63]	Not specified	Robotic bed consisting of a frame having 9 panels/boards that sit atop the frame, 3 underlying the head and back, 3 under the hips, and 3 below the legs of the patient that could turn a patient from side to side.	Torque sensors	Not specified
Andhare et al. [66]	Not specified	Automated lateral bed system composed of multiple panels for backrest raise and side turn.	Not specified	Not specified
Ezzet et al. [67]	Not specified	Mathematical modeling and simulation of a bed-chair system and a proposed automatic lateral turn method using PID and MPC controllers.	Not specified	Not specified
ProBed Co. [68]	Freedom Bed	Commercial bed operating mechanically through 3 separate platforms that were hinged together which could roll over a patient.	Not specified	5 to 30
Yousefi et al. [46] and Brush et al. [64]	Not specified	Bed consisting of a grid of smaller tiled units, each attached to an air bladder. A mechanical actuation mechanism of motors, gears, and rods would change the orientation of each unit separately to turn the patient.	Pressure sensor Temperature sensor Moisture sensor	0–60.9 for each tile

pneumatic manipulator that could slide under the body and tilt the user by pressurizing two pneumatic arms (Figure 3(i–k)). The device consisted of two soft tubular chambers fabricated out of thermally welded polyurethane rubber sheets. An electric motor and a pulley system were located inside one of the chambers where the motor could fold and extend the chamber's tip by controlling the length of a wire attached to the tip. When this chamber inflated, the manipulator could slide under the patient's body without friction and tilt the patient by pressurizing and bending the other chamber.

Transfer devices

Transfer devices were separated into four main categories based on the strategy that they use to transfer the patient: A) lifting, B) belt-driven, C) bed-to-bed/bed-to-wheelchair converting, and D) surface wave-distributing.

(A) Lifting devices

The first group of transfer devices lift the person from one support surface and transfer them to another location (Figure 4(a–e), Table 5). The first category of these devices are mechanical lift slings that are commonly used in healthcare settings including floor lifts that can be powered or non-powered, ceiling lifts, and wall lifts. Floor lifts [87] require a caregiver's guidance for lifting the patient. In the case of non-powered floor lifts, the caregiver needs to manually pump or turn a handle to raise the patient, which can be physically taxing on the caregiver. Ceiling lifts [88–90] require track rails, which will restrict transfers and access to any part of a facility that does not have a track installed. Moreover, if a patient falls while beyond track access, the ceiling lift is not useable. Wall lifts [91] are also installed on a wall, so they have a limited range of motion. A similar example of a foldable mechanical lift in the academic literature was also proposed by Kai et al. [79].

Some researchers have designed alternative lifting devices for transferring patients that can support the torso, lift the patient, keep them in a standing posture with/without the assistance of a caregiver, and finally transfer them [69–73,80–86,92]. Examples of two similar designs to assist with lifting the patient to transfer between a seated location and toilet were presented by Takahashi et al. [80–83] and Toyota Corporation [69] (Figure 4(a)). Both were designed such that the patient leaned forward and put their stomach on a padded platform while holding onto handles. The mechanism then lifted the user off of the seat. Takahashi et al. [80] proposed a device called KOMAWARI-SAN, which assumed the patient was already near the toilet and transferring from a wheelchair. The supported patient and lift mechanism were on a rotating base that allowed the patient to rotate between locations. The Toyota design [69] was commercialized in 2013 and used a wheeled platform for patient transfer from a bed to the toilet. Similarly, Asker et al. [84] proposed a similar device to the Toyota design with the difference that their device offered more DOFs which could position the shoulder and orient the trunk, with higher structural rigidity and payload capacity, as well as being able to assist in larger range of daily life tasks. In another work, Liu et al. [85] proposed a device similar to the Toyota design which imitated the motion of a caregiver who attempts to lift, hold, and transfer a patient on his back, but with a few differences. First it had 3 DOFs unlike Toyota which only had 2 DOFs. Second, it had a hip holder to prevent the patient from falling. Third, to achieve a more comfortable lift, an active stiffness control for chest holder motion control in combination with a passive cushion consisting of two columns of four air bladders, which could detect the applied force on the patient's chest to adjust the robot, was added to the system. A similar design was also proposed by Krishnan et al. [92] but with a few differences with Takahashi et al.'s work [80]. Unlike KOMAWARI-SAN which had two DOFs, their device had an extra translational DOF for adjusting the height of the lifting arm which facilitated reaching a comfortable standing or bending forward posture for the user.

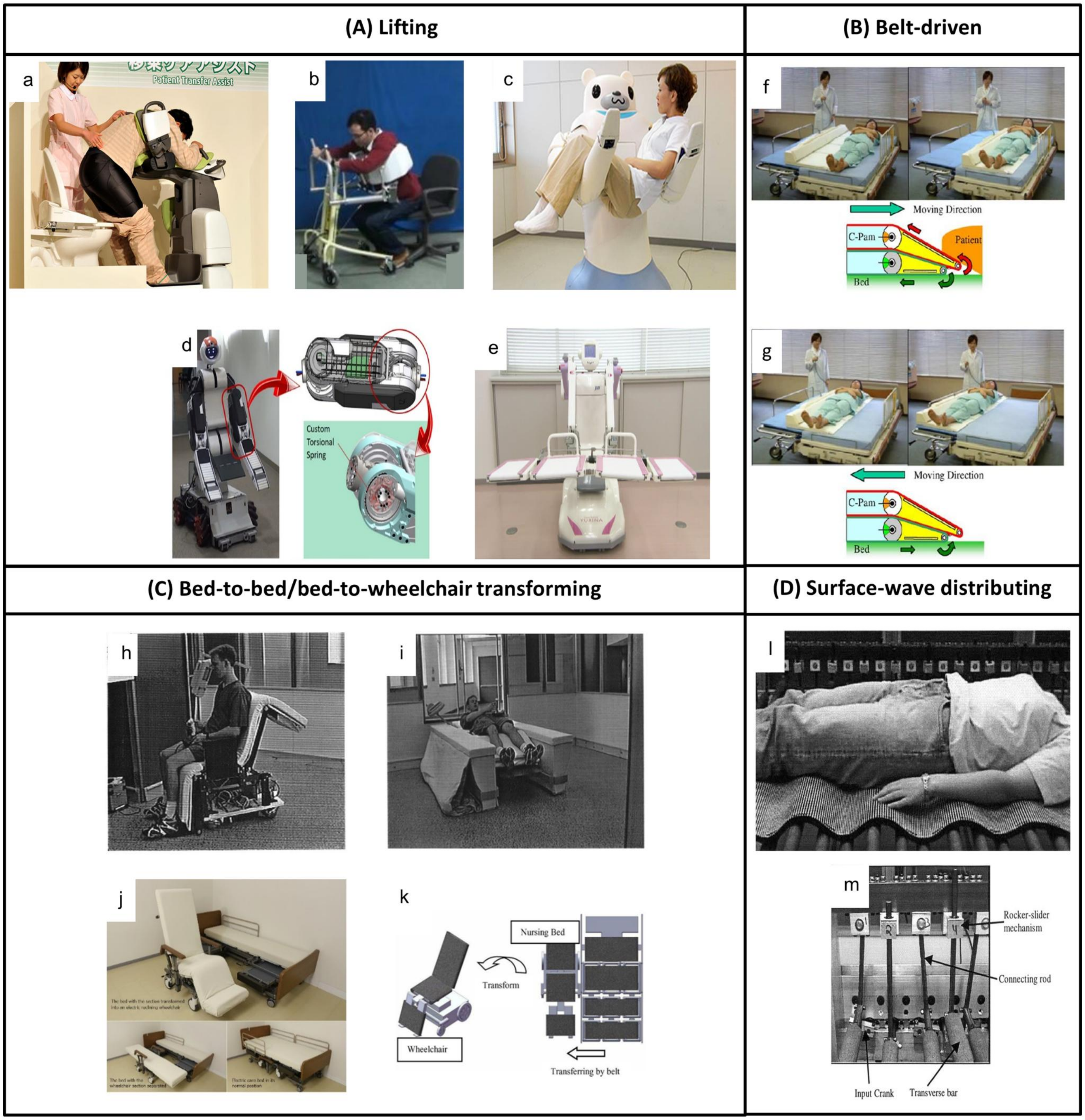

Figure 4. Transfer devices. (a) Commercially-available Toyota Patient Transfer-Assist Device [69], (b) pneumatic gripper with a novel slip-in tip adapted from Loh et al. [70], (c) RIBA by Mukai et al. [71], (d) RoNA by Ding et al. [72], (e) Commercially-available Yurina by Japan Logic Machine Co. [73], (f) C-Pam patient transfer apparatus by Wang and Kasagami [74] for moving the patient from the bed to the stretcher where the device moves to the right and slides under the patient body, (g) shows the device being pulled to the left by the caregiver to transfer the patient from the bed to the stretcher, (h) RHOMBUS by Mascaro et al. [75] in wheelchair mode, (i) RHOMBUS in bed mode, (j) Panasonic Resyone bed [76], (k) robotic bed proposed by Peng et al. [77], (l) surface traveling-wave generating bed proposed by Spano and Asada [78] with the body lying on bed of rocker-slider-crank mechanisms, and (m) details of rocker-slider-crank mechanism.

Additionally, to rotate the patient, their design was based on a planetary gear train for rotating the patient whereas in KOMAWARI-SAN, omni-directional wheels were used which could lead to slip. These solutions, however, require that the patient has sufficient lower limb and/or upper body strength to maintain the patient's torso on the padded platform. Loh et al. [70] proposed a wide multi-jointed gripper that grasped the torso of the patient, similar to how a human caregiver who would place their arms around the patient during a lifting motion (Figure 4(b)). The gripper had pneumatic shape-adaptive joints which allowed the gripper to conform to the user's body shape. The concept of adding a "slip-in tip" to both ends of the gripper was also proposed (earlier described in [65] under section IV.C, which is from the same research group led by Tsukagoshi), which allowed the gripper ends to slide in between the body and the support surface (i.e., chair backrest or bed).

Researchers have also proposed humanoid robots with thin arms that can slide under a person's body, lift, and transfer them to another location. Onishi et al. [86] proposed a humanoid robot called RI-MAN that could detect a specific person in real-time by

Table 4. Summary of pneumatic-electromechanical repositioning devices.

Reference	Device name	Device description	Sensors used	Tilt angle range (degrees)
Nakamura and Tsukagoshi [65]	Not specified	Two soft chambers and an electric motor that could slip in between the bed and the human body and turn the patient by bending a soft arm.	Pressure sensor Encoder Current sensor	Up to 90

Table 5. Summary of lifting transfer devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Kai et al. [79]	Not specified	Conceptual design and simulation of a foldable patient lift transfer system similar to the hospital hydraulic lifts with an attached seat support.	Not specified	100 Kg assumed in the simulation analysis. Never tested with a real patient.
Takahashi et al. [80–83]	Not specified	Two-DOF wheeled system with two supporting arms and a saddle for the patient to lean forward and put their belly on. The arms could lift the patient off the chair and transfer them.	EMG sensors Load cells Strain gauge	The device was able to transfer a male elderly who weighed 51 kg
Toyota [69]	Toyota patient transfer assist	Commercial transfer wheeled platform with two supporting arms for lifting and transferring patients.	Not specified	Not specified
Asker et al. [84]	Not specified	Assistive device consisting of two customized independently controlled 3-RPR parallel manipulators on a mobile wheeled platform serving as a walker used for different tasks such as sit-to-stand, walking assistance, as well as transfer from bed to chair.	Potentiometers	Intended to carry up to 3000 N and was tested using one subject but the weight not specified.
Liu et al. [85]	Piggyback transfer robot	Transfer device imitating the motion of a caregiver who attempts to lift, hold, and transfer a patient on his back, with a built-in tactile sensor including air bladders.	Pressure sensors	81 kg
Loh et al. [70]	Not specified	Robotic gripper that could slide under the patient's body, grip it, and transfer the patient to another location.	Not specified	The device was able to lift weights ranging from 63 kg to 85 kg
Onishi et al. [86]	RI-MAN	Humanoid robot that could detect a human in real time by audio and visual recognition and lift the patient by sliding its arms under the body.	Tactile sensors in arms	18.5 kg
Mukai et al. [71]	RIBA	Omnidirectional humanoid robot that could be guided by a caregiver's supervision to slide its arms under the patient's body and lift them.	Vision sensors (2 cameras) Audio sensors (2 microphones) Tactile sensors (on 128 points on each upper arm, 94 points on each forearm, 4 points on each hand, and 8 points on each shoulder pad)	63 kg
Ding et al. [72]	RoNA	Humanoid robot with a conveyor belt in the forearm that could slide under the patient's body and lift them.	Force sensors at the joints 3D vision sensors at the torso Tactile sensors at the arms and flap	500 lbs
Japan Logic Machine Co. [73]	Yurina	Commercial robot with two human-like arms and a bed mechanism attached to the arms. The arms connected to the torso and hip sections. The robot lifted the patient lying down on the bed.	Not specified	Not specified

audio and visual recognition, understand human speech, and perform human welfare tasks such as lifting a person. As reported by the researchers, limitations regarding the payload, motion accuracy, range of motion, and safety made RI-MAN an improper solution for real-life situations. To overcome these issues, Mukai et al. [71] from the same research group proposed a new robot called RIBA (Robot for Interactive Body Assistance) (Figure 4(c)), an omnidirectional robot with human-type arms that could be operated by a caregiver based on tactile guidance using a flexible tactile sheet mounted on the robot's body. Compared to RI-MAN, RIBA had a higher transfer payload capacity. Similarly, Ding et al. [72] developed a humanoid robot called RoNA (Robotic Nursing Assistant) (Figure 4(d)). Each arm had 7 actuated joints where a novel rotary series elastic actuator actuated all manipulator joints except for the forearm conveyor joint, providing a safe and compact design. The forearm had a conveyor belt and a compliant flipper mechanism that could slide under the body for patient safe handling with minimal shear forces and friction on the skin. The caregiver could move the forearm using a joystick and also manually adjust the arm under the patient. Yurina [73] is another

Table 6. Summary of belt-driven transfer devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Wang and Kasagami [74]	C-Pam (Careful Patient Mover)	Four modules, each having upper and lower units with belts similar to a conveyor belt. The caregiver could slide the device under the patient's body and transfer them between a stretcher and a bed.	Optical sensors	180 kg
Astir Technologies [93]	PowerNurse patient transferring device	Series of conveyor belts that could be inserted under the patient's body and transfer them.	Not specified	400 lbs
Kakutani et al. [94]	Not specified	Three pairs of upper and lower transfer plates with belts, where the caregiver would insert each plate under the patient's body to transport them.	Force sensor Torque sensor	100 kg
Tian et al. [95]	E-pat-plus (Easy Patient Transfer plus)	A belt pulley system consisting of four flat belts like a conveyor belt design that needs to be inserted under the patient body to transport them.	Not specified	Intended to transport up to 130 kg. Transported an adult but the weight was not specified.
Phillips [96]	Not specified	Frame, a mattress, and a chute where one end of the mattress would bend around a roller and extend into the chute. The patient could be transferred along the bed *via* a belt-driven system.	Not specified	Not specified

Table 7. Summary of bed-to-bed/bed-to-wheelchair converting transfer devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Mascaro et al. [75,97]	RHOMBUS	Holonomic omnidirectional mobile wheelchair convertible into a flat bed and vice versa to transfer the patient without posture change.	Force sensors Pressure sensors Displacement sensors Contact sensors	150 kg including the reconfigurable chair and other equipment of up to 50 kg
Panasonic [76]	Panasonic Resyone robotic bed	Bed with a detachable part morphing into a reclining wheelchair for transferring patient from bed to wheelchair.	Not specified	Not specified
Stiegelmeyer Co. [98]	Stiegelmeyer – Vertica bed	Commercial bed transforming into a sitting position to assist patients to stand up and also to transfer them.	Not specified	225 kg
Peng et al. [77]	Not specified	5-DOF main bed designed for posture change, and a one-DOF nursing bed for patient transfer. Both beds had belt-driven systems where the patient could be transferred from the main bed to the nursing bed. The nursing bed could be transformed to a wheelchair to transfer the patient.	Position sensors Encoders	Not specified

commercially available solution, similar to RIBA, with two human-like arms and a wheeled base that could operate *via* touch screen or voice recognition (Figure 4(e)). A bed mechanism was embedded in the robot's arms with a built-in conveyor belt mechanism that could be retracted or extended to transfer the patients along the bed as well.

(B) Belt-driven devices

These devices use a mechanism similar to a conveyor belt where the device either slides or is already under the individual's body and assist the caregivers to transfer them from one bed to another (Figure 4(f,g), Table 6). Examples of similar designs were presented by Wang and Kasagami [74], PowerNurse [93], Kakutani et al. [94], Tian et al. [95], and Philips et al. [96]. Wang and Kasagami [74] developed a transfer-assist device called Careful Patient Mover (C-Pam) with four modules, each consisting of upper and lower units with belts (Figure 4(f,g)). PowerNurse [93] is a commercial motorized thin low profile lateral transfer product that includes a series of conveyor belts for patient transfer. Kakutani et al. [94] developed a belt-driven transfer equipment, and Phillips [96] proposed a hospital bed equipped with a belt-driven system.

(C) Bed-to-bed and bed-to-wheelchair converting devices

The third group of transfer devices are bed-wheelchair systems where all or part of the bed can be converted into a wheelchair and vice versa to assist patient transfer without posture change while being transferred between the bed and the chair (Table 7). Mascaro et al. [75,97] developed a bed-wheelchair system called RHOMBUS (Reconfigurable Holonomic Omnidirectional Mobile Bed with Unified Seating) and equipped with a teleconferencing facility for patient and caregiver communication, where the wheelchair could be converted into a completely flat position and dock to its predefined location as a part of the bed (Figure 4(h,i)). Likewise, Resyone [76] is a commercial transfer-assist bed by Panasonic with voice recognition capability where part of the electric-powered nursing bed detaches and morphs to an electric-powered reclining wheelchair enabling transfer from bed to the wheelchair (Figure 4(j)). The Vertica Bed [98], which has a similar design to Resyone Bed [76], is also a similar commercial wheeled bed that can be transformed into a total sitting position to help the patient stand up and could also be used to transfer the patient. Peng et al. [77] also developed a multifunctional robotic bed which consisted of a main bed for posture change and a nursing bed for patient transfer each having a belt-driven system for patient transfer in between (Figure 4(k)).

Table 8. Summary surface-wave distributing transfer devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Finer and Asada [99]	Not specified	Standard mattress with an underlying array of coil springs that could generate a wave-like periodic motion to transfer the patient.	Pressure sensor	$22.5 \times 22.5\,cm^2$ object of 1 kg weight was transferred. No additional information on the weight range
Spano and Asada [78]	Not specified	Bed generating surface traveling waves *via* a mechanical actuation system consisting of a series of bars and slider-crank mechanisms for patient's transfer.	Not specified	This system successfully transported an infant of 10 kg

Table 9. Summary of combined devices for pressure relief and patient repositioning as well as patient repositioning and transfer.

Reference	Device name	Device description	Sensors used	Maximum tilt angle or transferred weight
Wilkinson et al. [101]	Not specified	A set of longitudinal cylindrical air cells in two sides that relieved the pressure under the body and turned the patient through inflation of the air cells in one side.	Pressure sensors	30 deg
Biggie et al. [102]	Not specified	A set of air cells for pressure-relief and two underlying sets of stacked bladders for turning the patient.	Not specified	40–50 deg
Votel et al. [103]	Not specified	Motor-winch assembly adjoined to a patient bed and connected to straps and hooks attached to a transfer sheet to transfer or reposition a patient.	Not specified	Not specified
Wei et al. [104]	Not specified	A set of vertical rods attached to a bed sheet as in a hammock to reposition the patient, and a set of linkages attached to the vertical rods for horizontal patient transfer.	Not specified	80 deg
Ning et al. [105]	Not specified	A robotic chair/bed system consisting of a reconfigurable and omnidirectional mobile chair/bed and a U-shaped bed. The wheelchair docked to the U-shaped bed and reconfigured to a static bed for transportation between chair and bed. Bed equipped with a flipping mechanism for patient rollover.	Contact sensors	96 deg 250 kg
Shafi et al. [106]	Not specified	A hydraulic wheeled hoist-typed lift mechanism with U-shaped bars attached to a bed sheet for patient repositioning and transfer.	Load cell	80 deg 600 lbs
Wang et al. [107]	Not specified	Similar to the commercial mechanical lift slings in healthcare institutions where the slings could be retracted *via* motors to tilt the patient. For patient transfer, the mechanical lift would lift the patient from bed and carry them.	Not specified	Not specified

(D) Surface wave distributing devices

Researchers from MIT have proposed the idea of generating traveling waves on the surface of a bed mattress to gently transport the body transversely or longitudinally along the mattress (Table 8). Finger and Asada [99] proposed a device that consisted of a standard commercial mattress with an underlying array of 32 coil springs actuated to create the wave motion that could move an object both vertically and along the mattress. A discrete-event control system was developed for coordinating and synchronizing the motions of the springs for moving a human object in an arbitrary direction and orientation. Similarly, inspired by the natural waves, Spano and Asada [78] built a bed prototype where 28 rocker-slider-crank actuation mechanisms with phase differences were used to create a traveling wave on the surface of the bed (Figure 4(l,m)). This system successfully transported an infant (10 kg, 66 cm) as a proof-of-concept. More detail on the designs of some of the introduced transfer technologies can be found in [100].

Combined solutions

The last group of devices for the prevention of PUs combine two of the capabilities of pressure relief, repositioning, and transfer which were classified into the following subcategories (Table 9).

A. Pressure relieving and repositioning devices

The first group of these devices both relieve the pressure and reposition the patient. These solutions are typically commercial pneumatic bed mattresses that consist of a set of air bladders which inflate and deflate to perform both tasks [19,101,102,108].

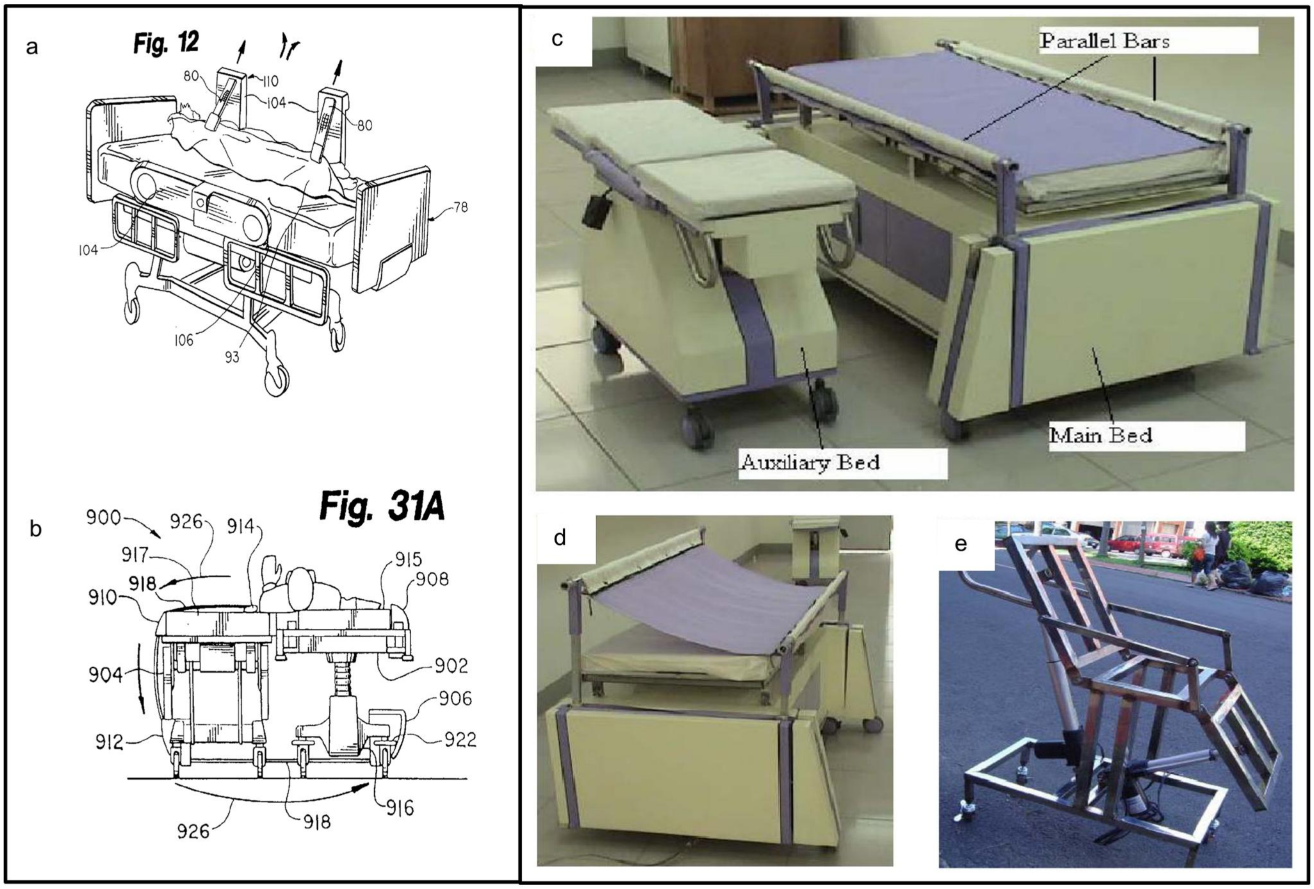

Figure 5. Combined repositing and transfer devices. (a) Patient rollover mechanism proposed by Votel et al. [103] with the straps (80) connected to the bed sheet (106) and attached to a retractable rollover member (104) activated through pulleys (not shown) for turning the patient, (b) shows patient transfer from the bed (902) to the adjacent cart (904) using a motor winch assembly (906), (c) hospital bed proposed by Wei et al. [104], (d) repositioning mechanism of the bed where two rods can move vertically in a hollow cylindrical structure to tilt the patient, and (e) the auxiliary bed that can be converted to a wheelchair for patient transfer.

Since this review paper is focusing on active devices, details on these passive devices are not included.

B. Repositioning and transfer devices

Another group of these devices can simultaneously perform repositioning and transfer. Votel et al. [103] proposed a portable patient pull up, rollover, and transfer device consisting of a motor-winch assembly that could be attached to a patient bed (Figure 5(a,b)). The motor-winch assembly connected to straps and hooks that attached to a transfer sheet to transfer or reposition a patient. Once the assembly was activated, the transfer sheet attached to the straps would retract to turn the patient. For transfer, the straps connected to a clamp and when the assembly was activated, the straps were retracted, and thus the patient moved laterally. In another design, Wei et al. [104] designed a hospital bed equipped with a lifting mechanism that included two parallel bars on the two sides of the bed, and a bed sheet attached to the bars where each bar was supported by two vertical rods at the ends (Figure 5(c–e)). Each supporting rod could move up and down in a hollow cylindrical structure, therefore tilting the patient. Additionally, the researchers developed a horizontal translation mechanism consisting of transverse rods that attached to the lifting mechanism and could translate it horizontally to transfer the patient from the main bed to the auxiliary bed. The auxiliary bed which was on wheels could be converted to a wheelchair for transferring patient from one location to another. A similar design was also proposed by Ning et al. [105] where they used the same transfer mechanism as Wei et al. [104] and a flipping mechanism for patient rollover. In another work, Shafi et al. [106] proposed a hydraulic motorized hoist on wheels, with two U-shaped bars each on one side of the patient, attached to a stretcher. For patient repositioning, the hydraulic motor would move one of the side bars to tilt the patient. For patient transfer, the device would lift the patient and was moved on wheels. Wang [107] designed a motorized device similar to a mechanical lift sling which is commonly used in healthcare institutions with a wheeled base. The slings hooked to shafts that could be rotated by a motor and attached to a bed mattress. To turn the patient, the motors would drive the shafts, thus, rolling the patient to one side. To transfer the patient, the device would lift a patient similar to the mechanical lift slings in hospitals.

Autonomy of the devices and pressure sensing technologies

A few research studies have attempted to monitor different risk factors associated with PUs such as pressure [40,109–128], temperature [129,130], humidity [131], blood flow [132], or a combination [28,46,131,133–147] to alert healthcare professionals if the individual is at the risk of developing a PU [148]. Some of these studies have used machine learning (ML) and artificial intelligence (AI) techniques to either detect/classify patient's posture and identify pressure distribution under the body, or perform ulcer tissue classification using image processing techniques and identify ulcer severity [149] which are further described in the following.

(A) Posture detection for pressure ulcer prevention

Posture detection has been done using various sensing technologies. Most studies have used pressure sensors [46,109–120,125,150,151] where a few studies have developed efficient repositioning schedule algorithms based on interface pressure measurements to minimize healthcare staff interaction with patients while preventing PU formation [110,113,114]. One study proposed a method for patient's posture detection from bed vertical reaction forces measured by using load cells [152]. One study used a combination of cameras and pressure sensors for posture detection [153,154]. Other researchers have attempted to use inertial sensors such as accelerometers and gyroscopes to identify an individual's posture [155,156]. Two major issues with vision systems are the lack of patient's privacy as well as significant reduction in the accuracy of camera systems in dark settings. Pressure sensors embedded in a bed mattress may affect patient's comfort and might not be an appropriate solution in healthcare settings. To address these issues, a few studies proposed the use of RF (radio frequency) signals for monitoring sleeping posture [157,158]. An example is the work by researchers from MIT [158] who proposed a wireless system, called BodyCompass, where they developed an ML algorithm to detect user's sleeping posture based on RF signals reflected from the person.

(B) Image processing for pressure ulcer detection

Researchers have also used imaging techniques to classify the ulcer tissue based on the injury size and shape and identified ulcer severity [159,160]. Typically, highly skilled personnel need to regularly examine the ulcer severity on-site. This regular monitoring is difficult to maintain due to nursing shortages in healthcare settings and additionally, consistency in diagnosis from various experts might not be achieved. Therefore, imaging techniques can be used for telemonitoring and early preventive measurement purposes and could also remove the subjective clinical diagnosis through AI. An example is by Chang et al. [160] who developed a portable multimodal sensing probe where they integrated five sensing modalities including RGB, three-dimensional depth, thermal, multispectral, and chemical sensing for real-time wound assessment.

Discussion

This review began with the aim of understanding the state-of-the-art assistive technologies that relieve pressure ulcers (PUs) in bed/wheelchair-reliant patients. Specifically, assistive devices for pressure ulcer prevention were classified into four main categories: (I) pressure-relieving, (II) repositioning, (III) transfer, and (IV) combined solutions (Figure 1, Tables 1–9). While there exists a number of devices in each category from both academia and industry, there are some challenges that hinder widespread adoption. Common drawbacks in most of these devices are the design complexity, lack of patient comfort, and a lack of autonomy requiring caregivers to intervene frequently. However, the last decade has witnessed tremendous advancements in robotics, sensors, perception, user-centered design, and autonomous systems. Thus, the advancements in assistive technologies for pressure ulcer relief could lie at the intersection of these fields.

Active pressure-relieving devices suffer from a tradeoff between pressure reduction site specificity and complex design (Figure 2 and Table 1). Most mattresses and seat cushions consist of several arrays of individually actuated air cells that need to be coordinated and controlled to adapt to the patient's body shape contours, making the mechanical design bulky and controls cumbersome [22–45]. Furthermore, most of these devices have only focused on reducing the normal forces that are applied on the user's body and not shear forces which also contribute to PU development. Therefore, there is a need to tailor both the normal forces and shear forces of contact between the body and the bed. The emerging field of soft robotics has demonstrated several novel actuators, and variable stiffness structures that could lead to more compact yet site specific solutions. Novel manufacturing techniques that include multi-material additive manufacturing (MMAM) could reveal larger design possibilities [161,162]. Furthermore, particle jamming (a physical process in which a flexible membrane is filled with a granular material resulting in a change of the stiffness with the application of vacuum) combined with pneumatics could also allow engineers to design novel soft actuators with controllable shape and stiffness [163]. MMAM and particle jamming techniques can result in the fabrication of novel stiffness-controllable soft actuators that have the potential to be integrated into a bed mattress or a seat cushion to allow site-specific pressure redistribution under the patient body.

Repositioning devices which include motorized hospital beds and mechanical slings also have a few limitations (Figure 3 and Tables 2–4). Motorized hospital beds [46,47,62,68] are expensive and may not be compact especially in small constrained spaces. Mechanical slings have to be operated under a caregiver's supervision and might cause patient discomfort and skin abrasion. Future research direction may include incorporating autonomy in repositioning while simultaneously maximizing user comfort.

Transfer devices also have several major drawbacks (Figure 4 and Tables 5–8). Non-powered commercial mechanical lifts are required to be operated by a caregiver *via* a handle which can be a physically demanding task for the staff. Ceiling lifts [88–90] have small footprints but will restrict transfers and access to any part of a facility that does not have a track installed. Wall lifts [91] also have to be installed on a wall; therefore, they have a limited range of motion. The other serious drawback of mechanical lifts is patient safety since the patient might drop if the sling size and type are not customized to the patient. The other issue is that the patient must bend and compress in the slings which could be painful and frustrating. Lifting arms [69,70,80–85,92] (Figure 4(a,b)) require that the patient has sufficient lower limb and/or upper body strength to maintain the patient's torso on the padded platform. Humanoid robots [71–73,86] (Figure 4(c–e)) proposed by the robotics community are another solution, but some have a limited payload capacity and are not widely accepted by their users [86]. Belt-driven devices [74,93–96] (Figure 4(f,g)) have to be slid under the individual's body and pulled to transfer the patient to a different bed. Therefore, they can still place a physical burden on caregivers. Converting bed-to-bed or bed-to-wheelchair devices [75–77,97,98] (Figure 4(h–k)) are bulky and expensive and will not work well in healthcare settings with a limited space. Among the two surface-wave distributing solutions, one study [78] built a bed where they used 28 rocker-slider-crank mechanisms with phase shifts to generate the traveling wave on the bed surface which was a relatively complicated mechanical system (Figure 4(l,m)). Additionally, none of the proposed devices could transfer an adult, and further research is needed to investigate the possibility of using traveling waves for patient transfer.

Another major drawback of existing transfer devices is that they can only transfer the patient off the bed; they fail to help adjust the patient's position on the bed such as moving a patient who has slid down the bed. In summary, cost, bulkiness, lack of autonomy, and failure to adjust the patient's position anywhere on the bed are major issues in most transfer devices. Therefore, future research direction should focus on developing affordable and compact transfer devices that can move the patient anywhere on the bed to help caregivers with transferring bed-reliant patients. One possible future idea could include investigating the potential of developing a cost-effective soft and compliant mechanism as part of a custom bed mattress that creates a traveling wave in two dimensions (both along the bed length and width) to move the patient on the bed plane with minimal physical effort from the caregiver.

Lastly, among combined solutions and to the best of the authors' knowledge, there is not a combined solution that can autonomously and continuously identify pressure concentrations to reduce pressure on the body parts, reposition the patients, and move the patient to the edge of the bed to assist with transfers (Figure 5 and Table 9). Long term pressure ulcer relief cannot be accomplished using a single method, and may require a combination of local pressure redistribution, repositioning, and transfer. The next generation devices could leverage machine learning techniques to distribute between the three tasks to minimize the overall caregiver's effort, while maximally delaying the onset of pressure ulcers. Future research opportunities include investigating the potential of developing a soft pneumatic bed mattress consisting of an array of air bladders that can be inflated and deflated periodically to (1) offload pressure from the body, (2) reposition the patient frequently, and (3) generate a traveling wave on the bed surface to move the patient anywhere on the bed The combination of the first two ideas is available in commercial mattresses as discussed in section XI.A and seems to be promising. The idea of using traveling waves for patient transfer was also proposed in a bed design [78]. However, further research is needed to investigate the potential of developing a cost-effective soft and compliant mechanism as part of a custom bed mattress that creates a traveling wave to move the patient on the bed with minimal physical effort from the caregiver.

In terms of pressure distribution sensing and posture detection technologies, pressure sensors embedded into the support surface might affect the user's comfort [40,109–128], and vision-based sensors [153,154] for patient posture detection are privacy-intrusive. Moreover, in most cases, an array of smaller pressure sensors (such as commercial pressure sensing mats) is embedded to the support surface to create a map of the pressure distribution which can be expensive and requires a complicated hardware for data processing. Most importantly, none of these techniques have been integrated into pressure relieving and repositioning devices to create a fully autonomous device to automatically act without the caregiver's intervention. Future research could be dedicated to developing novel non-invasive, low-cost, wearable sensors with minimal hardware usage for posture detection and pressure ulcer risk factor measurements.

Lastly, existing examples discussed within this discussion illustrate an opportunity in that the devices are clearly focused on the mechanical advantage rather than blending the functionality with the human experience. The authors acknowledge that assistive technologies need to satisfy functional and supra-functional needs (i.e., social, aspirational, cultural, and emotional.) equally. Ensuring a balanced product outcome relies upon a deeper understanding of users' needs, including the products they surround themselves with, their vernacular, and ways in which we can connect with their values. Human-centered design provides a bridge between the functional needs and the needs of the users. Without a user-centered design approach, assistive technology even if purchased can later become abandoned, under-used or misused. Therefore, future research should focus on the holistic needs to ensure a balanced design outcome. Conducting user needs studies concurrently with the development of technology enables design opportunity to be identified that are firmly based in the context of our users we aim to serve.

Conclusions

This review paper classified and investigated the existing research-level and commercial assistive technologies for pressure ulcer prevention in terms of their mechanical design, actuation methods, control strategies, sensing technologies, and device autonomy. In particular, the devices were categorized into four categories including pressure-relieving, patient repositioning, patient transfer, and combined solutions where each category was further subcategorized as well. The review results suggest that design complexity lack of patient comfort, and lack of autonomy requiring caregivers frequent intervention are the key challenges that prevent the existing technologies for widespread acceptability and use. Future advancements in assistive technologies for pressure ulcer mitigation could lie at the intersection of robotics, sensors, perception, user-centered design, and autonomous systems.

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