EXPLORING PATIENT PRESSURE RELIEF, REPOSITIONING AND TRANSFER WHILE IN A BED

BY

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THESIS

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ABSTRACT

Patients with limited body movement ability are subject to the development of pressure ulcers (PUs), especially when confined to a bed. Pressure relief and frequent repositioning help to mitigate complications associated with PUs. Manually moving a patient is a physically-demanding task that can lead to musculoskeletal disorders for the caregivers and skin abrasion for patients. The first study in this thesis reviewed devices (commercially-available or published research) that are meant to address patient pressure relief, repositioning and/or transfer while in a bed. The review findings indicated that current technologies have limitations such as design complexity, high cost, bulkiness, unidirectional patient transfer, and the need for a caregiver's intervention.

Inspired by waves in nature such as water waves that can carry objects, a proposed solution in the literature for patient transfer is to create traveling ways on a bed surface for multidirectional patient transfer and to minimize the caregiver's physical effort for constant patient readjustment on the bed. Inspired by this idea, the second study in this thesis built upon prior work in the literature and presented the design requirements for moving a human body using traveling waves on a bed surface. Particularly, through kinematic analysis and simulation of traveling waves, this study explored how various wave parameters such as the wavelength, amplitude, frequency, and number of wave-generating actuators would affect human transportation speed and movement smoothness. Results are summarized into a set of design guidelines for the development of actuation systems to physically realize a traveling wave that can move a body on a bed.

ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

1.1 BRIEF OVERVIEW OF TECHNOLOGIES FOR PATIENT PRESSURE ULCER MITIGATION, REPOSITIONING AND TRANSFER WHILE IN A BED

Individuals with a limited body movement ability such as patients with a loss of mobility due to spinal cord injury, frailty from aging, obesity, stroke, and severe injury due to an accident are prone to the development of pressure ulcers (PUs), also known as a bedsores [1],[2]. Negative physical, psychological, and social consequences affecting health and well-being of individuals such as increased morbidity and mortality, pain, discomfort, depression, lowered autonomy and security, and impaired social functioning are only some of the complications associated with PUs [3],[4].

To mitigate the development of PUs, immobile individuals are expected to perform frequent pressure relief and frequent repositioning in their body posture such that the pressure under the body is maintained to be less than 32 mmHg [5],[6]. Wheelchair users are encouraged to perform pressure-relieving exercises every 15-20 minutes [7] while patients in bed are expected to be repositioned to a different body side every two hours [8] to a tilting angle of 30° [9]. However, due nursing labor shortages in healthcare institutions or commitments of in-home family caregivers, adherence with this frequent manual repositioning is difficult to be maintained [10]. Manual repositioning, transferring, and lifting patients are physically strenuous tasks that can result in skin abrasions or patient falling, and cause musculoskeletal disorders for the caregiver [11].

Several research-level and commercial assistive devices have been proposed in the literature to reduce the development of pressure ulcers and assist caregivers with constant patient repositioning and transferring. These devices provide assistance with pressure relief, repositioning, transferring, or a combination of these strategies. 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 (e.g., [27]-[41]). Repositioning devices can roll the patient from one side to the other side (e.g., [8], [43]-[59]). Transfer devices help caregivers move patients in and out of beds or wheelchairs(e.g., [60]-[86]). Combined strategies merge pressure relief and patient repositioning, or patient repositioning and patient transfer capabilities (e.g., [87]-[93]).

Most literature reviews on pressure ulcer mitigation technologies 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. To the best of our knowledge, no comprehensive literature review has been done that explores the existing technologies from an engineering perspective, in terms of their mechanical design, actuation methods, control strategies, sensing technologies, and device autonomy.

1.2 MOTIVATION FOR EXPLORING METHODS TO MOVE OR TRANSFER PATIENTS ON A BED SURFACE

Our work started with reviewing the existing assistive technologies for pressure ulcer mitigation in the literature. Design complexity, high cost, bulkiness and the need for a caregiver's intervention are major drawbacks of current technologies. Additionally, no devices have been developed that can relieve pressure, reposition, and transfer the patient simultaneously. To address these issues, the initial idea of our work was to design and fabricate a soft pneumatic bed mattress that could autonomously relieve the pressure, reposition, and transfer the patient on the bed surface.

As we will discuss in Chapter 2, our review of existing technologies found that there exist commercial mattresses that can perform pressure relief and patient repositioning, but not patient transferring. Furthermore, one of the main limitations of current patient transfer technologies is that they can only transfer the patient in one direction and fail to reposition a patient who has moved into an undesired position on a bed surface. Therefore, a solution is needed for multidirectional patient transfer on a bed surface that could potentially be integrated into a commercial bed mattress with already available pressure relief and patient repositioning capabilities.

One proposed solution for patient transfer in the literature is to create traveling waves on a bed surface which was found to minimize the caregiver's effort for patient transfer as well as assist with moving the patient anywhere on the bed surface [86. This idea has been further generalized to moving objects (and not necessarily the human body) in the literature. In the following section, we will overview traveling-wave generating mechanisms in more detail and discuss the limitations that exist.

1.3 USING TRAVELING WAVES TO MOVE OBJECTS

Inspired by natural waves such as water waves that can carry objects, and the peristaltic motion of biological creatures such as caterpillars that can create a waveform on the surface of their soft body, researchers and product developers have proposed the idea of using traveling waves to move objects. Recently, some researchers have used reconfigurable surfaces called peristaltic tables that can generate wave-like surface profiles for object transportation.

Peristaltic tables are defined as two dimensional surfaces that are discretized into an array of height-adjustable actuators that can be controlled independently to change the surface topology and roll or slide an object in a desired direction [12]. Compliant handling of delicate objects and simultaneous manipulation of multiple objects make peristaltic tables an attractive solution for transporting delicate parcels in industrial applications [13]. An example is Festo's WaveHandling system [14] which relies on a network of pneumatic bellows under a flexible membrane that deform the surface and create a wave motion for targeted transportation and simultaneous sorting of rolling objects (Figure 1.1(a)). In another study, Mosadegh *et al.* [15] developed a braille-display-controlled manifold of soft blisters and used an array of 32 expandable soft chambers to move a ball as a proof-of-concept (Figure 1.1(b)). However, both of these systems could only move round objects.

To address this issue, other peristaltic tables were proposed which could move flat objects without rolling. Robertson *et al.* [12] proposed a modular reconfigurable surface consisting of a 4×4 grid of linear vacuum-powered soft pneumatic actuators which could move vertically to transport a ball and a steel block (Figure 1.1(c)). In another work and inspired by the locomotion of a caterpillar in the nature, Deng *et al.* [13] proposed a novel soft peristaltic table consisting of a grid of inflatable soft air chambers that could move small flat objects such as a smart phone with three degrees of freedom (DOFs) (two planar and one rotational) by surface deformation through the inflation of chambers (Figure 1.1(d)). Similarly, Onoe *et al.* [16] designed a pneumatic linear actuator made from flexible rubber with four chambers, which was an improvement of a previous actuator developed by the researchers. By controlling the pressure inside each chamber independently and sequentially, an elastic deformation was generated which was used for small-scale object propulsion. Other researchers have used non-pneumatic actuation mechanisms to move the object on the surface as well. Recently, Raptis *et al.* [17] conceptualized and assembled a morphing surface consisting of a grid of electromechanical linear actuators that could autonomously adjust the surface topography to convey an arbitrary number of objects to a reference point.

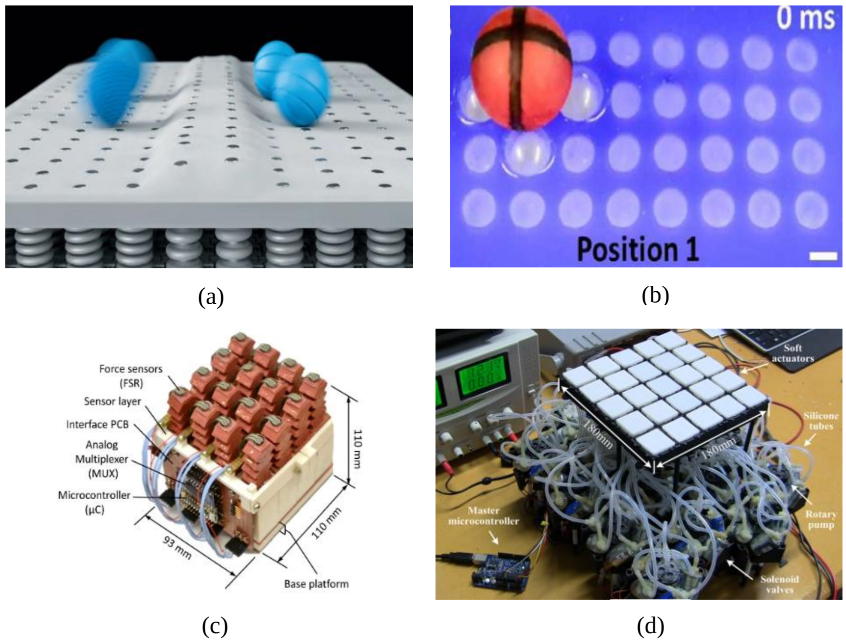


Figure 1.1 Examples of peristaltic tables in the literature. (a) WaveHandling system by Festo Co. [14]. (b) Braille display soft machine by Mosadegh *et al.* [15]. (c) Modular soft table by Robertson *et al.* [12]. (d) Soft robotic table inspired by a caterpillar's locomotion by Deng *et al.* [13].

Inspired by the gastropod's locomotion, Watanabe and Tsukagoshi [18] developed a pneumatic soft sheet actuator called "wavy-sheet" which consisted of three rubber tubes covered in fabric that could generate continuous traveling waves throughout the whole soft body. By fixing one end of the actuator, the actuator was able to transport a flat object (Figure 1.2). Similarly, Salem *et al.* [19] fabricated a soft robot with an embedded pneumatic network with two pressure inlets which were controlled to generate bidirectional traveling waves in the body of the robot (Figure 1.3). A model-based method based on the kinematics of a traveling wave was also presented to design and generate bidirectional traveling waves in soft structures. The robot performance was experimentally validated and compared to the model.

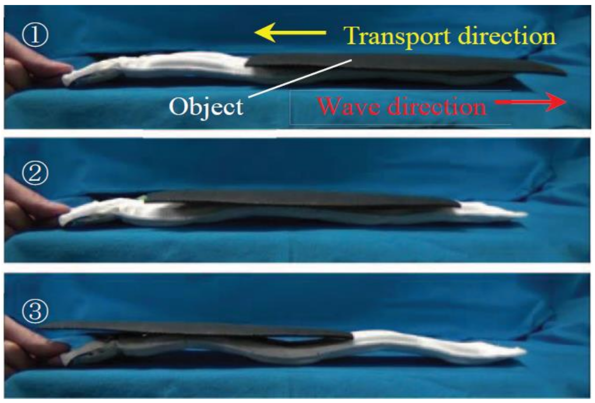


Figure 1.2. Wavy-sheet actuator by Watanabe and Tsukagoshi [18]

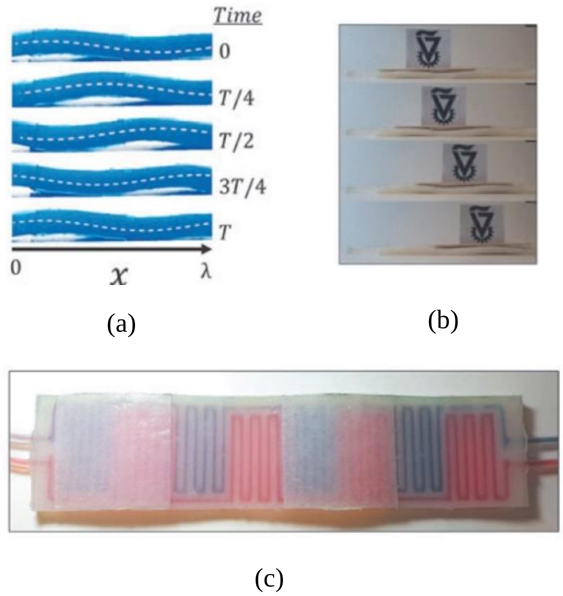


Figure 1.3. Soft robot with a bidirectional traveling wave developed by Salem *et al.* [19]. (a) Shows the robot moving during one cycle (b) Shows one end of the robot is kept fixed and the object is moved to the right on top of the robot, and (c) Robot's top view which shows the two inlet pressure channels (shown in red and blue) that are used to create traveling waves in two directions.

One of the main barriers to the adoption of peristaltic tables in the industry is their control and dynamic modeling. The independent control of the high number of the actuators used in a peristaltic table and the nonlinearities of the soft material used in soft tables make it difficult to accurately manipulate the object on the surface. The modeling of the dynamics and kinematics of soft materials is also challenging because of the high degrees of freedom of a soft material [20]. To address these issues, some researchers have used numerical methods such as finite element analysis [21] and discrete element method [22], [23] to model soft peristaltic tables. However, numerical methods are often time-consuming and only applicable to a specific design [24]. To address these issues, other researchers have proposed data-driven models which are based on machine learning and reinforcement learning algorithms to model soft peristaltic tables and control the object movement ([20], [24]–[26]). The idea is to see what the actuation pattern as well as the magnitude of the input signal to the embedded actuators in a soft table should be to generate a specific shape on the surface of the table such that the object is moved in a desired direction. However, one of the limitations of machine learning algorithms for soft tables is that it is computationally expensive to cover all possible shapes on the surface of the table and a large number of training examples is required [25].

Most of the work that has been done in the literature rely on experimental approaches where researchers have built a system of specific type of actuators capable of generating a traveling wave and conducted experiments to show that their system can move an object. There are very few papers that have introduced actuator-agnostic system design requirements for object transportation via a traveling wave (e.g., how one should pick the number of actuators to generate a traveling wave, what the size of the actuator should be, how fast the actuators should move, etc.).

1.4 THESIS ORGANIZATION

Chapter 1 gives a brief overview of the existing technologies for pressure ulcer mitigation, repositioning and transferring from a bed among immobile individuals, their limitations, and the gaps especially in terms of patient transfer. Our review findings suggest that using traveling waves to move a human body on a bed surface seems to be a promising solution for multidirectional patient transfer. We review traveling wave-generating mechanisms in the literature for the general purpose of object transportation in the context of peristaltic tables and the gaps that exist in the literature.

In Chapter 2, we (1) review, 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, and (3) discuss the significant technical challenges that need addressing and (4) identify potential design opportunities for future innovations.

Chapter 3 establishes design guidelines for moving a human body via surface traveling waves through kinematic analysis and simulation of a traveling wave. Particularly, this chapter explores how various parameters such as the wavelength, wave amplitude, wave frequency, number of wave-generating actuators, and their movement pattern would affect human transportation speed and movement smoothness. The study presents a set of design requirements which can help engineers to develop actuation systems capable of creating traveling waves to not only transport a human body anywhere on the bed surface, but also to move any type of objects. The limitations of the study are discussed and suggestions for future work are also given.

Chapter 4 summarizes the design guidelines for transferring a human body on a bed via surface traveling waves established by this study.

CHAPTER 2: REVIEW OF ASSISTIVE DEVICES FOR THE PREVENTION AND MITIGATION OF PRESSURE ULCERS AMONG IMMOBILE PATIENTS

2.1 ABSTRACT

Pressure ulcers (PUs) are areas of localized damage to the skin and underlying tissues due to compression, shear, or a combination. 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. Compliance with regular repositioning is difficult to maintain due to nursing labor shortages or constraints of in-home caregivers. Manual repositioning, transferring, and lifting of immobile patients are physically demanding tasks that can lead to musculoskeletal disorders for the caregivers and skin abrasion or falling for patients. To reduce the development of PUs and to assist caregivers with these tasks, several commercial and academic research devices have been developed to assist with pressure relief, repositioning, transfer, and/or a combination. This chapter categorizes and investigates these existing technologies in terms of their mechanical design, actuation methods, control strategies, sensing technologies, and device autonomy. Challenges that hinder widespread acceptability and use of current technologies are design complexity, lack of patient comfort, and a lack of autonomy requiring caregivers to intervene frequently. This chapter discusses significant technical limitations that still need to be addressed and identifies potential design opportunities. Advancements in assistive technologies for pressure ulcer mitigation could lie at the intersection of robotics, sensors, perception, user-centered design, and autonomous systems.

2.2 INTRODUCTION

A pressure injury, also known as a pressure ulcer (PU), bedsore, pressure sore, or decubitus, 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 [3]. These include increased morbidity and mortality, pain, discomfort, depression, lowered autonomy and security, and impaired social functioning [4]. In the United States, the cost of pressure injury care was estimated to approach $11.6 billion annually (in the period between 2000 to 2012) with an individual patient care cost ranging between $500 and $152,000 depending on the wound severity, hospitalization duration, clinical settings, etc. [1].

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 hours at the heels and sacrum of patients may cause necrosis [5],[6]. Wheelchair users are encouraged to perform pressure-relieving exercises every 15-20 minutes [7]. Patients in bed are expected to be repositioned to a different body side every two hours [8], and a tilt of 30° is considered sufficient for offloading [9]. 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 [10]. 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 [11].

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. 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 (Figure 2.1).

In this chapter, we classify current assistive technologies for pressure ulcer mitigation among individuals with a limited body movement ability into four categories in terms of their mechanical design, actuation systems, sensing technologies, control architectures, and device autonomy: 1) pressure-relieving, 2) repositioning, 3) transfer, and 4) combined devices. Each device category will be further categorized into subcategories. Limitations that still need to be addressed will be discussed and potential design opportunities will be identified. As will be explained, among transfer technologies, the idea of using traveling waves seems to be a promising approach. Therefore, in this chapter, traveling-wave generating actuation systems that go beyond human body transfer that can move objects in general, will also be investigated and their limitations will be discussed.

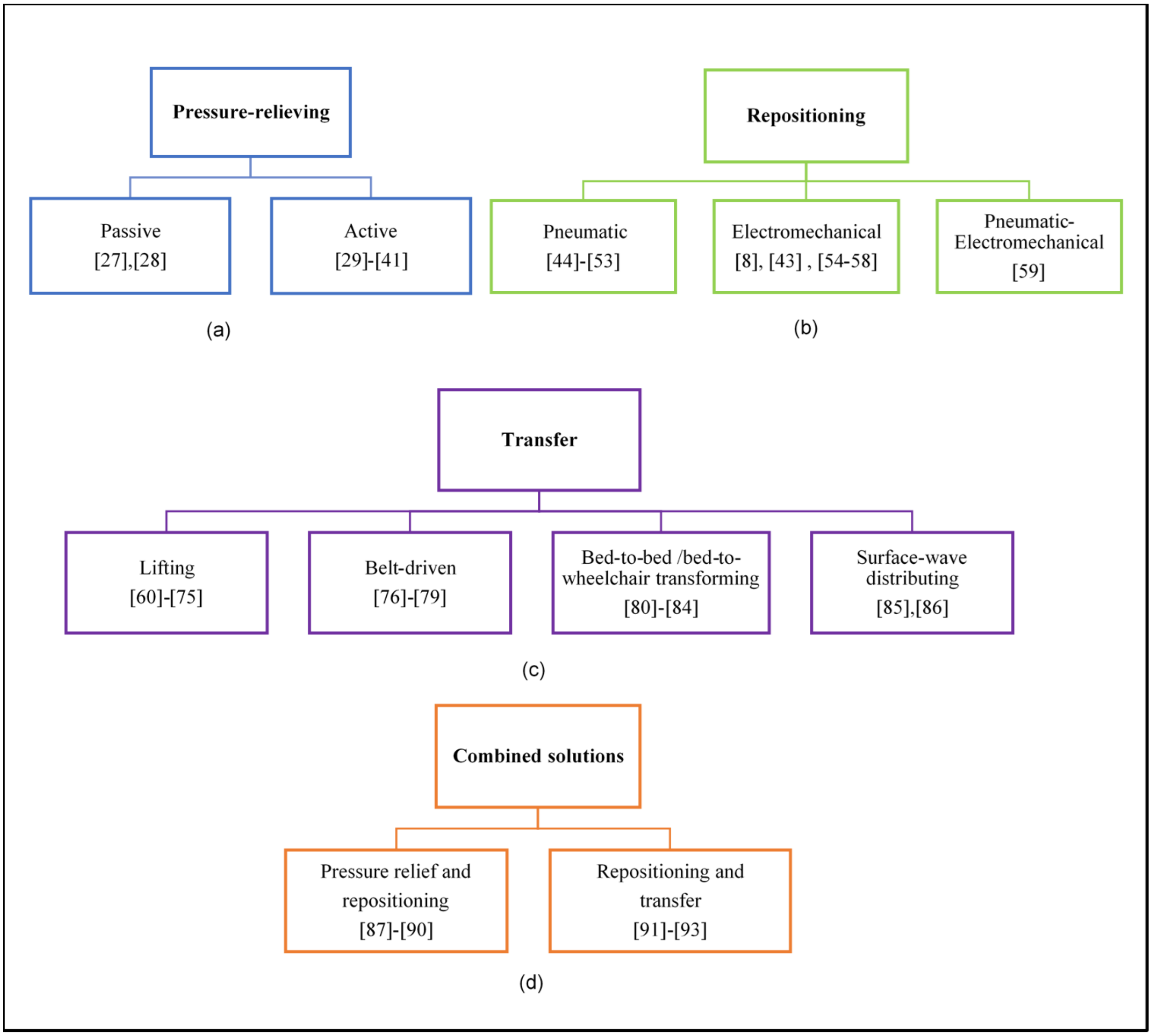


Figure 2.1. Proposed classification categories of assistive devices for prevention of pressure ulcers among immobile individuals. Relevant references are cited within square brackets.

2.3 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.

2.3.1 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 offloading the pressure [2]. Most passive devices are commercial (e.g., [27], [28]) and there are very few recent research papers that have focused on passive devices (Figure 2.1(a)). This paper focuses on the active devices which are described in the next subsection.

2.3.2 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.

A majority of active devices use pneumatic pressure modulation systems to reduce the pressure (Figure 2.2 and Table 2.1). 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 [29]–[32] (Figure 2.2(a)). Some products cycle through predefined pressures [15],[31], while others monitor and distribute pressure across large regions of the body [29]. Similarly in the academic literature, Moon *et al.* [33] 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.* [34] 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 2.2(b)). Similarly, Carrigan *et al.* [35] (Figure 2.2(c)) and Nakagami *et al.* [36] developed seat cushions which could offload pressure from specific sites under the body. In another design, Fiedler *et al.* [37] 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 2.2(d)). The system continuously and locally monitored the patient's skin condition and inflated and deflated the air bladders to raise and lower the pins to conform to the user's body shape.

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.* [38] conceptualized a seat cushion, called IntelliPad, constructed from an array of dome-shaped silicon rubber actuators each having three chambers (Figure 2.2(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 only experimentally demonstrated the force distributing capability of 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.* [39] developed a foam mattress consisting of an array of smaller cells where each was independently and vertically actuated using a motorized system for local pressure distribution change under different body parts. Yu *et al.* [40] 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 2.2(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.

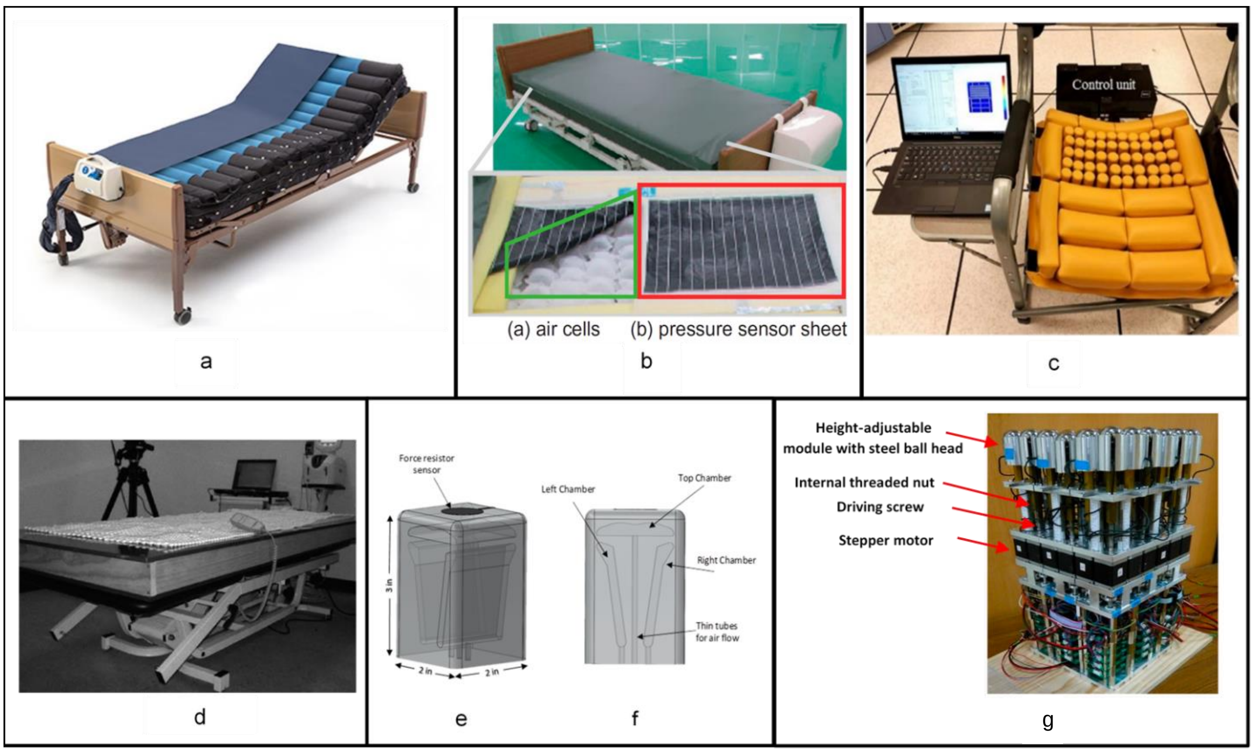


Figure 2.2 Active pressure-relieving devices. (a) Commercially-available Invacare Corporation bed mattress [31], (b) bed mattress proposed by Takashima et al. [34], (c) automated pressure-mapping and modulating seat cushion by Carrigan et al. [35], (d) IANSiS bed prototype by Fiedler et al. [37] (e) 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. [38], and (g) proposed pressure-relieving seat cushion using modularized height-adjustable system adapted from Yu et al. [40].

Table 2.1. Summary of active pressure-relieving devices

Reference	Device name	Device description	Sensors used
Moon *et al.*, 2005 [33]	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.*, 2014 [34]	Not specified	Air mattress consisting of 49 air bladders made from 2-stack arrays with overlying pressure sensor mat.	Capacitive pressure sensors
Carrigan *et al.*, 2019 [35]	Not specified	Seat cushion made from array of 62 cylindrical and rectangular air bladders.	Pressure sensors
Nakagami *et al.*, 2015 [36]	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
Fiedler *et al.*, 2009 [37]	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 40×40 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
Elfehri *et al.*, 2011 [39]	Not specified	Air mattress made from array of 10×20 air cells with embedded pressure sensors.	Pressure sensors
Raeisinezhad *et al.*, 2020 [38]	IntelliPad	Proposed seat cushion design that would consist of array of 9×9 dome-shaped silicon rubber actuators (overall size of cushion: 410×460 mm^2). Each actuator having 3 chambers independently pressurized and controlled horizontally and vertically to redistribute normal and shear forces.	Force sensitive resistor
Yu *et al.*, 2014 [40]	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.*, 2020 [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

2.4 REPOSITIONING DEVICES

Repositioning involves rolling the patient to a side and supporting the body at an incline so as to not be lying on ulcerated locations. Generally, repositioning is done with passive 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 [42] to motorized tilting hospital beds [43]. 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.

2.4.1 PNEUMATIC DEVICES

These devices use pneumatic actuation strategies to turn the patient (Table 2.2, Figure 2.3(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 [44]–[53] (Figure 2.3(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 [47]–[52] (Figure 2.3(b)). An example of this category is Chugo *et al.*'s work [52] 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 2.3(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 were then inflated to incline toward the side they were trying to move. Another example is the Toto Lateral Turning System [53] (Figure 2.3(d)). This commercial automated system consists of two arrays of air bladders in the right and left sides with three longitudinally-folded rigid sheets on top 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.

2.4.2 ELECTROMECHANICAL DEVICES

These devices employ electromechanical actuation strategies to turn the patient (Figure 2.3(e)-(h), Table 2.3). Commercial devices include motorized tilting hospital beds such as Multicare Bed [43], which can automatically rotate around the longitudinal axis of the bed (Figure 2.3(e)). However, they are expensive and bulky. Among research studies, a bed prototype, called Marionette Bed, was designed and built, where a bed sheet was secured into overhead rollers and the patient was supported as in a hammock (Figure 2.3(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 [8] [54]. 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.* [55] 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 2.3(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. Similarly, the commercially-available Freedom Bed [56] operates mechanically through bending 3 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 2.3(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. An individual tile unit prototype was manufactured and open-loop controlled as a proof-of-concept [57][58].

2.4.3 PNEUMATIC-ELECTROMECHANICAL DEVICES

One study used a combination of electromechanical and pneumatic actuation methods to roll the patient over (Figure 2.3(i)-(k), Table 2.4). Nakamura and Tsukagoshi [59] proposed a soft pneumatic manipulator that could slide under the body and tilt the user by pressurizing two pneumatic arms (Figure 2.3(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 was inflated, the manipulator could slide under the patient's body without friction and tilt the patient by pressurizing and bending the other chamber.

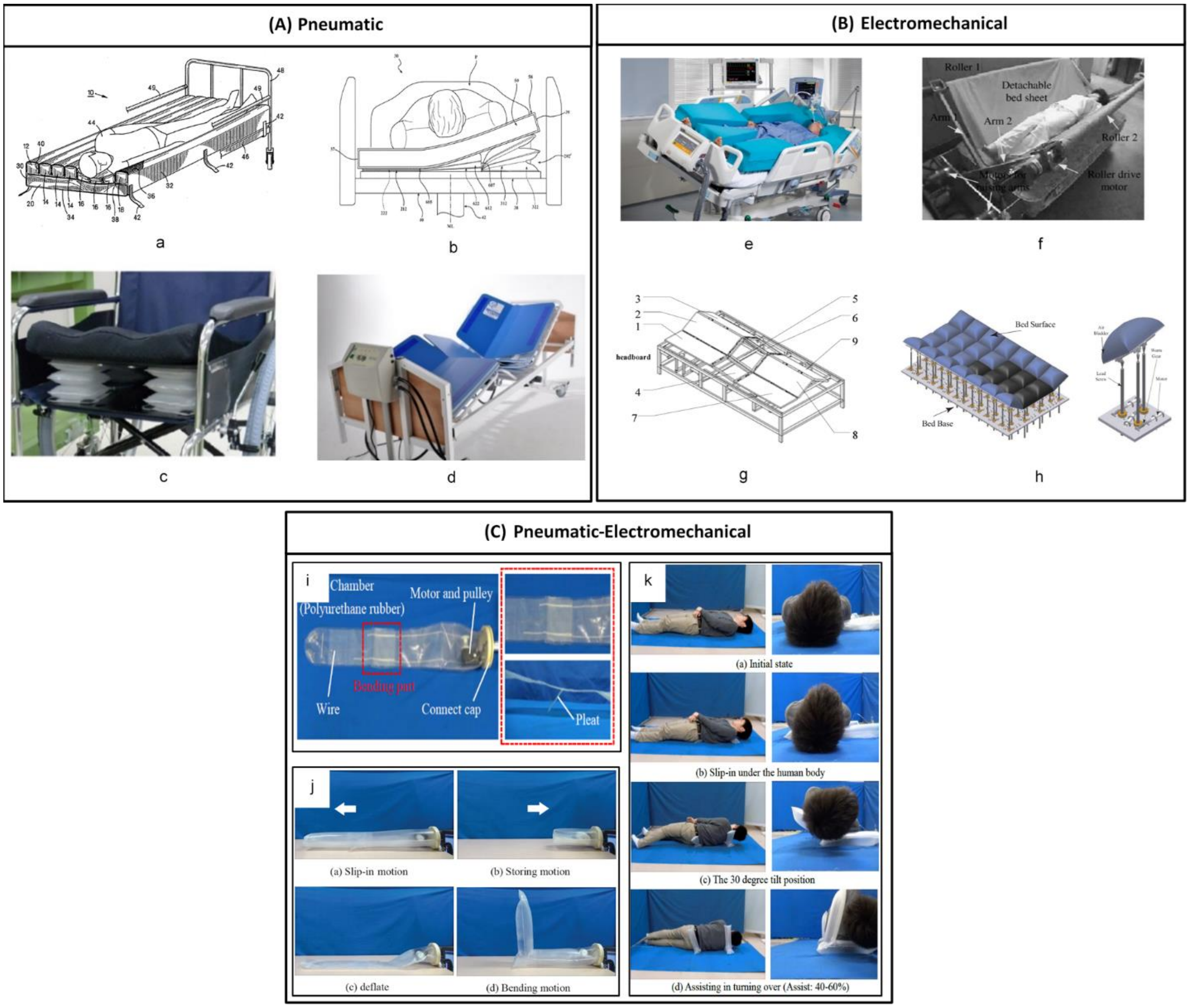


Figure 2.3. Repositioning devices. (a) Bed mattress proposed by Bodine et al. [45], (b) turning apparatus by Galer et al. [51] where multiple air bladders were stacked to increase patient's tilting angle, (c) depressurization assistance system by Chugo et al. [52], (d) commercially-available Toto Lateral Turning System [53] (e) commercially-available Linet Multicare bed [43], (f) Marionette Bed by [23],[54], (g) robotic nursing bed by Tan et al. [55], (h) smart bed platform by [57],[58] (i) components of the repositioning device based on a soft pneumatic slip-in manipulator by Nakamura and Tsukagoshi [59], (j) overview of manipulator motions, and (k) steps to turn the patient over.

Table 2.2. Summary of pneumatic repositioning devices

Reference	**Device name**	**Device description**	**Sensors used**	**Tilt angle range (degrees)**
Hasty *et al*. 1994 [44]	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*., 1994 [45]	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. [46]	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 [47]	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 [48]	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*., 2000 [49]	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 [50]	Ekamove	Automated, sensor-controlled commercial dual air chamber placed under a support surface to turn the patients.	Not specified	0-30
Galer *et al*., 2019 [51]	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*., 2011 [52]	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 [53]	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

Table 2.3. Summary of electromechanical repositioning devices.

Reference	Device name	Device description	Sensors used	Tilt angle range (degrees)
Linet Co. [43]	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, 2002 [54] and Roy *et al.*, 2003 [8]	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.*, 2009 [39]	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
ProBed Co. [56]	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.*, 2011 [57] and Brush *et al.*, 2013[58]	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

Table 2.4. Summary of pneumatic-electromechanical repositioning devices.

Reference	Device name	Device description	Sensors used	Tilt angle range (degrees)
Nakamura and Tsukagoshi, 2018 [59]	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

2.5 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.

2.5.1 LIFTING DEVICES

The first group of transfer devices lift the person from one support surface and transfer them to another location (Fig 2.4(a)-(e), Table 2.5). 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 [60] 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 [61]–[63] 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 [64] are also installed on a wall, so they have a limited range of motion.

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 [65]–[71]. 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.* [65]–[68] and Toyota Corporation [69] (Figure 2.4(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.* [65] 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. A similar design was also proposed by Krishnan et al. [70] but with a few differences with Takahashi et al.'s work [65]. 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. 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.* [71] 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 2.4(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 (which was earlier described in the proposed pneumatic-electromechanical repositioning device by Nakamaura et al. [59] from the same research group), 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.* [72] proposed a humanoid robot called RI-MAN that could detect a specific person in real-time by 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.* [73] from the same research group proposed a new robot called RIBA (Robot for Interactive Body Assistance)(Figure 2.4(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.* [74] developed a humanoid robot called RoNA (Robotic Nursing Assistant)(Figure 2.4(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 [75] is another 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 2.4(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.

2.5.2 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 2.4(f),(g), Table 2.6). Examples of similar designs were presented by Wang and Kasagami [76], PowerNurse [77], Kakutani *et al.* [78], and Philips et al. [79]. Wang and Kasagami [76] developed a transfer-assist device called Careful Patient Mover (C-Pam) with four modules, each consisting of upper and lower units with belts (Figure 2.4(f),(g)). PowerNurse [77] is a commercial motorized thin low profile lateral transfer product that includes a series of conveyor belts for patient transfer. Kakutani *et al.* [78] developed a belt-driven transfer equipment and Phillips [79] proposed a hospital bed equipped with a belt-driven system.

2.5.3 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 2.7). Mascaro *et al.* [80],[81] 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 2.4 (h),(i)). Likewise, Resyone [82] 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 2.4(j)) The Vertica Bed [83] 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.* [84] 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 2.4(k)).

2.5.4 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 2.8). Finger and Asada [85] proposed a device that consisted of a standard commercial mattress with an underlying array of 32 coil springs that were 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 [86] 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. 2.4(l),(m)). This system successfully transported an infant of 10 kg weight and 66 cm height as a proof-of-concept.

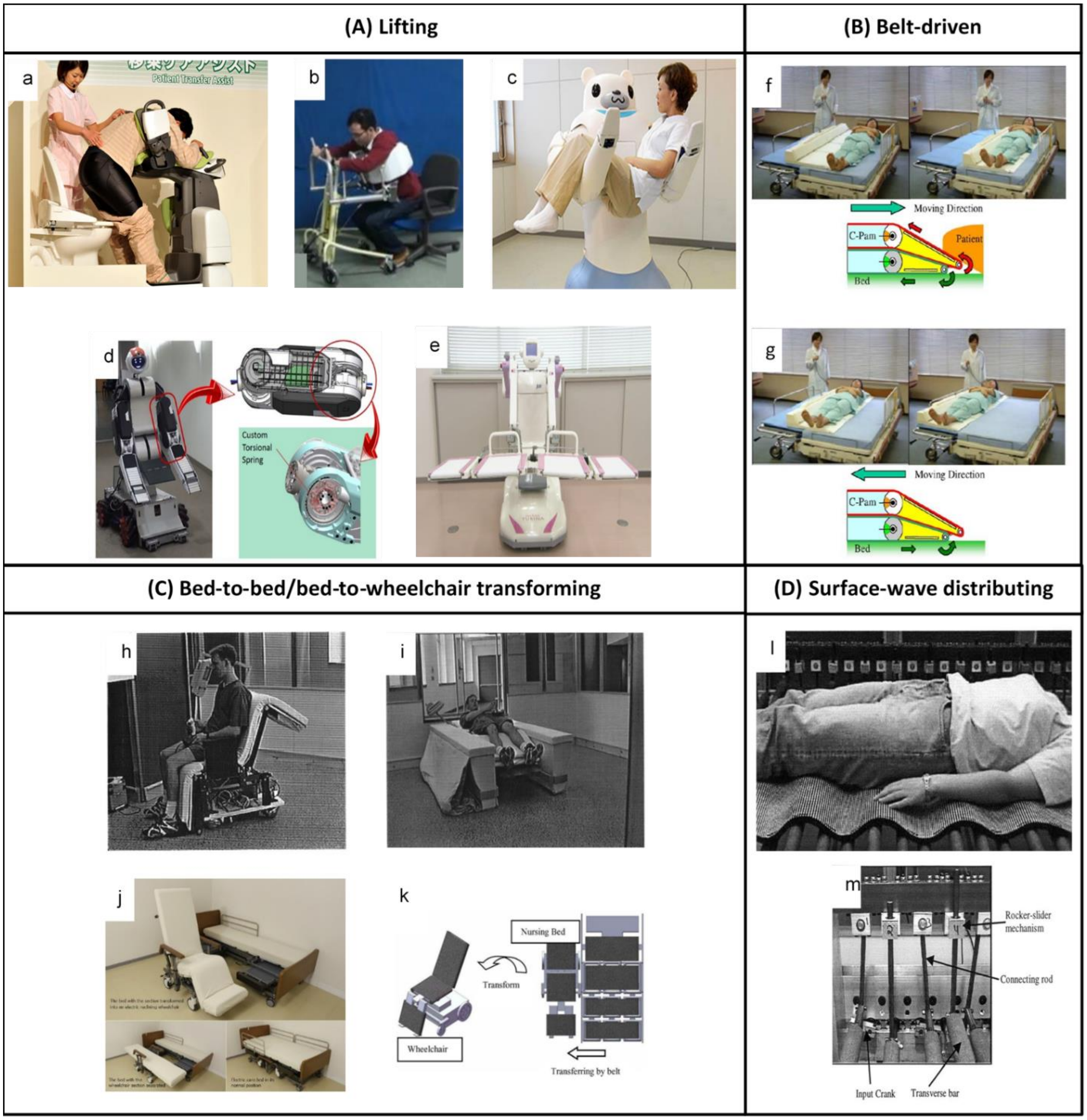


Figure 2.4. Transfer devices. (a) Commercially-available Toyota Patient Transfer-Assist Device [69], (b) pneumatic gripper with a novel slip-in tip adapted from Loh et al. [71], (c) RIBA by Mukai et al. [73], (d) RoNA by Ding et al. [74], (e) Commercially-available Yurina by Japan Logic Machine Co. [75], (f) C-Pam patient transfer apparatus by Wang and Kasagami [76] 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. [65] in wheelchair mode, (i) RHOMBUS in bed mode, (j) Panasonic Resyone bed [82], (k) robotic bed proposed by Peng et al. [84], (l) surface traveling-wave generating bed proposed by Spano and Asada [86] with the body lying on bed of rocker-slider-crank mechanisms, and (m) details of rocker-slider-crank mechanism.

Table 2.5. Summary of lifting transfer devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Takahashi *et al.*, 2003 [65]–[68]	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 51kg
Toyota [69]	Toyota patient transfer assist	Commercial transfer wheeled platform with two supporting arms for lifting and transferring patients.	Not specified	Not specified
Loh *et al.*, 2014 [71]	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.*, 2007 [52]	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.*, 2010 [73]	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.*, 2014 [74]	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. [75]	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

Table 2.6. Summary of belt-driven transfer devices

Reference	Device name	Device description	Sensors used	Maximum transported weight
Wang and Kasagami, 2008 [76]	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, 2012 [77]	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.*, 1995 [78]	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
Phillips, 2019 [79]	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 2.7. Summary of bed-to-bed/bed-to-wheelchair converting transfer devices

Reference	Device name	Device description	Sensors used	Maximum transported weight
Mascaro *et al.*, 1997 [80]	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 [82]	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. [83]	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.*, 2010 [84]	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

Table 2.8. Summary of surface wave distributing devices.

Reference	Device name	Device description	Sensors used	Maximum transported weight
Finer and Asada, 1999 [85]	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	22.5×22.5 cm^2 object of 1 kg weight was transferred. No additional information on the weight range
Spano and Asada, 2000 [86]	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

2.6 COMBINED SOLUTIONS

The last group of devices for the prevention of PUs combine two of the capabilities of pressure relief, repositioning, and transfer which are broken down into the following subcategories (Table 2.9).

2.6.1 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 ([87]–[90]).

2.6.2 REPOSITIONING AND TRANSFER DEVICES

Another group of these devices can simultaneously perform repositioning and transfer. Votel *et al.* [91] 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 2.5(a),(b)). The motor-winch assembly was connected to straps and hooks that could be attached to a transfer sheet to transfer or reposition a patient. Once the assembly was activated, the transfer sheet which was attached to the straps would retract to turn the patient. For transfer, the straps were connected to a clamp and when the assembly was activated, the straps were retracted, and thus the patient moved laterally. In another design, Ching-Hua *et al.* [92] 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 2.5(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 were 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. Wang [93] designed a motorized device similar to a mechanical lift sling which is commonly used in health care institutions with a wheeled base. The slings were hooked to shafts that could be rotated by a motor and were 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.

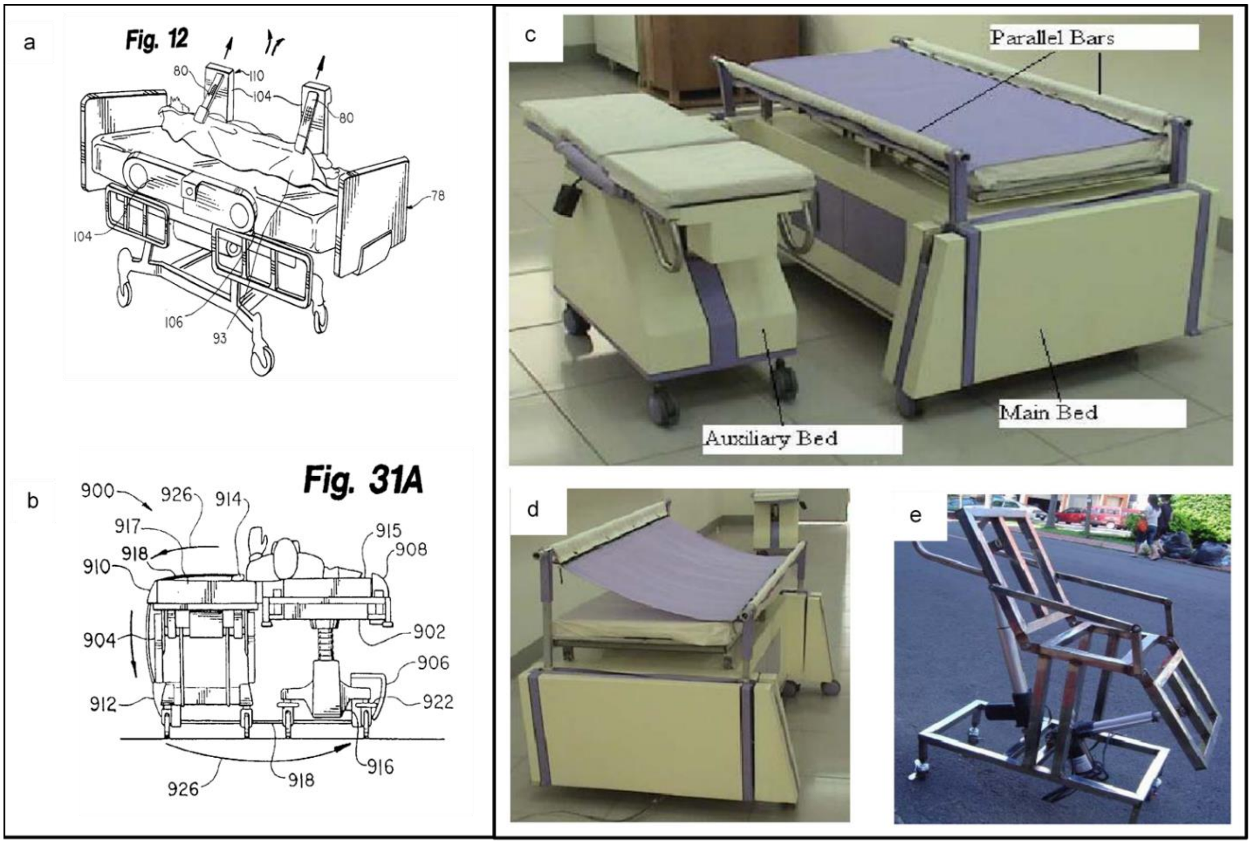


Figure 2.5. Combined repositing and transfer devices. (a) Patient rollover mechanism proposed by Votel et al. [91] with the straps (80) connected to the bed sheet (106) and attached to a retractable rollover member (104) activated through pulleys (not shown) for turning the patient, (b) shows patient transfer from the bed (902) to the adjacent cart (904) using a motor winch assembly (906) (c) hospital bed proposed by Ching-Hua et al. [92], (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.

Table 2.9. 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*., 1996 [89]	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*., 2010 [90]	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.*, 2004 [91]	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
Ching-Hua *et al.*, 2007 [92]	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
Wang *et al.*, 2016 [93]	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

2.7 AUTONOMY OF DEVICES AND PRESSURE SENSING TECHNOLOGIES

A few research studies have attempted to monitor different risk factors associated with PUs such as pressure [41], [69]–[85], temperature [111],[112], humidity [113], blood flow [114], or a combination [33],[57],[115]–[123] to alert healthcare professionals if the individual is at the risk of developing a PU [124]. 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 [125] which are further described in the following.

2.7.1 POSTURE DETECTION FOR PRESSURE ULCER PREVENTION

Posture detection has been done using various sensing technologies. Most studies have used pressure sensors [57],[69]–[80],[85] 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 [95],[98],[99]. One study used a combination of cameras and pressure sensors for posture detection [126]. Other researchers have attempted to use inertial sensors such as accelerometers and gyroscopes to identify an individual’s posture [127]–[129]. 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. Besides, pressure sensor 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 papers have proposed the use of RF (radio frequency) signals for monitoring sleeping posture which could also be used for PU prevention [130],[131]. An example is the work by researchers from MIT [131] 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, which has the potential to prevent PUs.

2.7.2 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 [132],[133]. 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. An example of this type is the work by Chang *et al.* [133] 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.

2.8 DISCUSSION AND FUTURE RESEARCH DIRECTIONS

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 2.1, Tables 2.9-2.1). While the paper reviews a number of devices in each category from both academic literature and commercial products, there are some challenges that hinder widespread acceptability and use. A common drawback in most of these devices is 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 2.2 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 [13]-[27]. 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 soft additive manufacturing could reveal larger design possibilities. Multi-material additive manufacturing (MMAM) is a technique that enables engineers to manufacture parts consisting of multiple materials each having their own unique properties [132]. 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 [133]. MMAM and particle jamming techniques can result in the fabrication of novel stiffness-controllable soft actuators which 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 2.3 and Tables 2-4). Motorized hospital beds ([27], [39], [41], [42]) are expensive and may not be an appropriate solution in small places. Mechanical slings have to be operated under a healthcare professional's supervision and might cause patient discomfort and skin abrasion. Future research direction may include

Transfer devices also have several major drawbacks (Figure 2.4 and Tables 2.5-2.8). 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 ([61]–[63]) have small footprints but will restrict transfers and access to any part of a facility that does not have a track installed. Wall lifts [64] 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 slings are not of the right size and type for the patient. The other issue is that the patients must bend and compress themselves in the slings which could be painful and frustrating. Lifting arms ([65]–[71])(Figure 2.4(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 ([72]–[75])(Figure 2.4(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 [72]. Belt-driven devices ([61]-[64]) (Figure 2.4(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 ([65]-[69])(Figure 2.4(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 [86] 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 2.4(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 the idea 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 2.5 and Table 2.9). Long term pressure ulcer relief cannot be accomplished using a single method, and may require a combination of local pressure redistribution, repositioning, and transfer. It is well known that pressure relief requires the least effort both from the device as well as caregiver, while repositioning and transfer require the most effort. 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 could be to investigate the potential of the idea 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 2.6 and seems to be promising. The idea of using traveling waves for patient transfer was also proposed in a bed design [86]. However, further research is needed to investigate the potential of the idea 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 [57], [95]–[102], [110], and vision-based sensors [126] 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 functional 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 be also dedicated to focusing 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.

CHAPTER 3: DESIGN GUIDELINES FOR MOVING A HUMAN BODY ON A BED USING TRAVELING WAVES[1]

3.1 ABSTRACT

Inspired by natural waves such as water waves that can carry objects, this study presents the design requirements for moving a human body on a bed using traveling waves. Particularly, through kinematic analysis and simulation of a traveling wave, the study explores how various wave parameters such as the wavelength, wave amplitude, wave frequency, number of wave-generating actuators, and their movement pattern would affect human transportation speed and movement smoothness. Results suggest that transportation speed is linearly proportional to wave frequency. Additionally, to increase movement smoothness, wave amplitude and wavelength should be reduced, while the number of wave particles should be maximized. However, there is a tradeoff between the number of actuators that can be used and the complexity of system's design and control. Furthermore, at a maximum, the wavelength should be less than half of the object length to ensure motion stability while also exceeding a certain critical value to guarantee that feasible waves are achieved in practice. Additional requirements for moving an elastic object, such as a human body, were also established with regard to the minimum stiffness of the interface layer between the body and the wave particles.

3.2 INTRODUCTION

Patients lying on a bed with limited personal body movement ability need assistance from caregivers for transfers and repositioning. For example, they may need to be moved to the edge of

[1] Portions of this chapter are published in the Design of Medical Devices Conference proceeding: Mansouri, M., Krishnan, G., and Hsiao-Wecksler, E.T. "Design Guidelines for Moving a Human Body on a Bed Using Traveling Waves", 21st Annual Design of Medical Devices Conference, April 11-14, 2022. (4 pages)

the mattress for transfer from the bed to a wheelchair, or they may need to be readjusted on the mattress if they slid down when the head of the bed is elevated. Common transfer practices are to manually support and move the patient or to use sliders or transfer sheets under the patient body and manually pull the device to move the patient [11]. Manually moving a patient is a physically demanding task that can lead to musculoskeletal disorders for the caregivers and skin abrasion for patients [11]. To address these issues, alternative devices for patient transfer have been proposed. Commercial technologies include mechanical lifts [61]–[64] or conveyor belts [77] that reduce the physical effort of the caregiver. Research-level devices include humanoid robots that can lift and move a person ([72]–[75], weight-supporting mechanical arms that can grab a person from the waist and lift them [65], [71], and bed-to-wheelchair converting devices where part of the bed is transformed into a wheelchair for patient transfer [80]–[84]. However, these devices have several limitations, such as design complexity, high cost, bulkiness, the need for a caregiver's intervention, and unidirectional patient transfer (as with conveyor belts). Another major drawback of existing devices is that they are generally external devices that must be brought over to the patient and implemented only when there is a need to transfer the patient off the bed. No devices have been developed to address the need to reposition, perhaps in multiple directions, the patient that has moved into undesired positions on the bed.

Inspired by natural waves such as water waves, Spano and Asada from MIT [86] created a partial bed surface where a series of slider-crank mechanisms were used to create a wave to move a body in one direction to the edge of the bed. Additionally, they proposed a set of design guidelines for patient transfer using these surface waves. The idea of moving patients via traveling waves seems to address some of the limitations of current transfer technologies and it can also minimize the caregiver's physical effort and need for constant readjustment.

Inspired by this idea, the goal of this study was to build upon their prior work and investigate actuator-agnostic design requirements for moving a human body using traveling waves in multiple directions. More specifically, the objective was to understand how a traveling wave is generated and how different wave parameters such as the wavelength, frequency, amplitude, number of wave-generating actuators, and their movement pattern would affect transportation speed and movement smoothness. In this study, we do not dictate the type of actuator design that is needed to generate the wave motion. Rather the motion generated by an actuator is represented by the motion of a 'wave particle', as a wave particle is a way to visualize the motion of the combined wave front. Therefore, this study will explore a more comprehensive set of design requirements for moving the human body around a bed surface using traveling waves (Figure 2.1). Furthermore, these design requirements are intended to be agnostic to the actuator type.

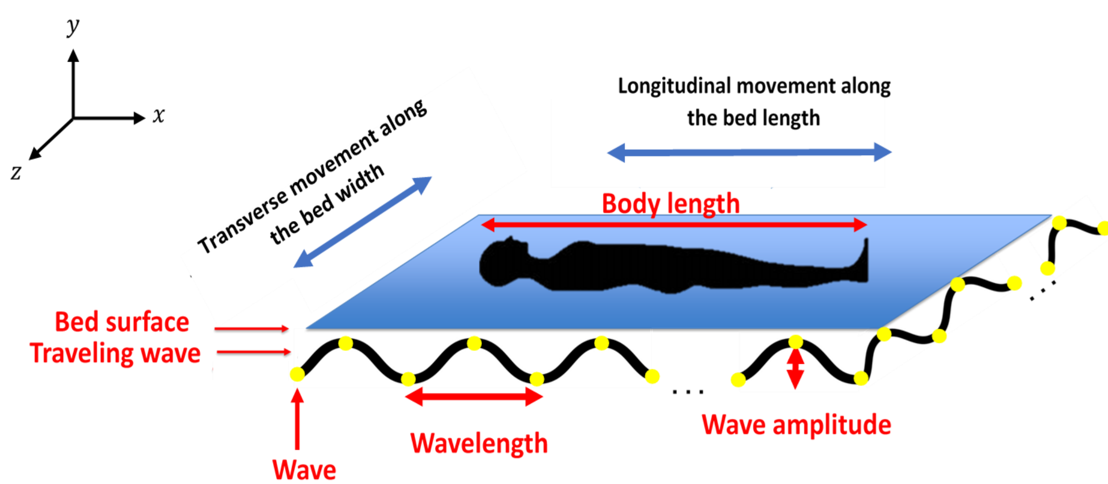


Figure 3.1. Schematic of moving a human body on the surface of a bed using traveling waves in two dimensions.

3.3 METHODS

3.3.1 KINEMATIC ANALYSIS OF A TRAVELING WAVE

In this section, we present a kinematic analysis of a traveling wave to explain how a traveling wave is generated and how 1) transportation speed and 2) movement smoothness are affected by the wave parameters. In this analysis, we assume that the object is rigid. In section 3.5, we will explore additional requirements that are needed to move an elastic object, such as the human body.

3.3.1.1 TRANSPORTATION SPEED ANALYSIS

The problem is defined as the following, as was proposed in [86]. We would like to move an object of mass M and with length L (Figure 3.2(A)). The traveling wave has an amplitude A and wavelength λ, and consists of individual wave particles. The wavelength is the distance between two continuous crests or troughs, and it is dictated by the spacing between wave particles. A wave particle is defined as following an elliptical trajectory centered at u with minor and major axes of r and R, respectively (Figure 3.2(B)) (note that $A = R$). The parameter u is the x coordinate of the center of each wave particle's elliptical trajectory. To move the object to the right, each particle has a repeated pattern: starting from the left quadrants of the ellipse, the particle moves clockwise upward, contacts the object, supports and slightly raises the object, detaches from the object, moves downward, and finally returns to its original position. All wave particles follow the same trajectory but with a phase difference θ_0 with respect to their adjacent particle where $0 < \theta_0 < \pi$. (In Figure 3.2(A), we have only shown the trajectory of three particles.) The number of wave particles n in one wavelength is $\frac{2\pi}{\theta_0} + 1$. As a result of synchronization between the motion of different wave particles, the wave is generated, and the object is transferred to the right.

Since the motion of each particle is periodic, the x and y coordinates of the particle change as a function of time and can be written as

$$x_p(u,t) = u + r sin\theta(u,t) \quad (1)$$

$$y_p(u,t) = R cos\theta(u,t) \quad (2)$$

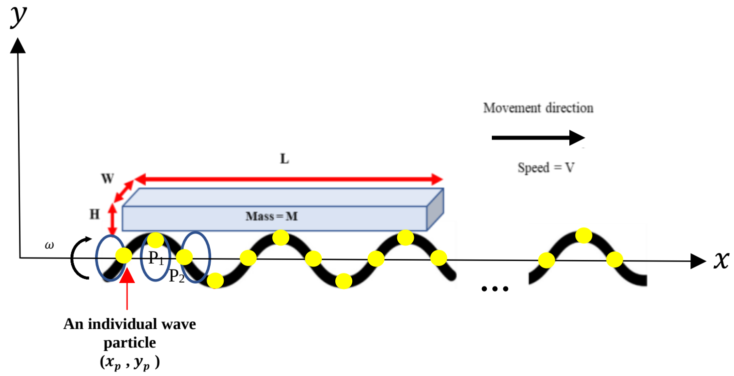
where $\theta(u,t)$ is shown in Figure 3.2(B) and is given by

$$\theta(u,t) = \omega t + \frac{2\pi u}{\lambda} \quad (3)$$

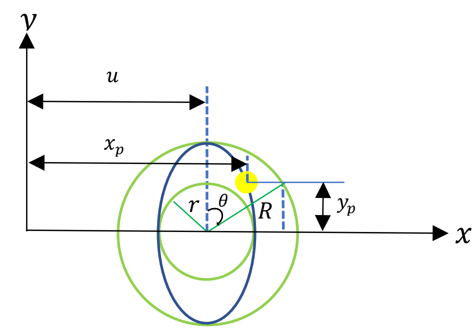
In Equation (3), ω is the frequency of the cyclic motion (in this case in the clockwise direction). We assume the object is rigid and is only supported at the wave crests. Furthermore, we assume that there is no slipping between the object and the contacting wave particle. To calculate the transportation speed, we differentiate $x_p(u,t)$ with respect to time and compute it at the wave crest where $\theta(u,t) = 0$ (Equation (4)).

$$V_{transportation} = \frac{\partial x_p}{\partial t}|_{\theta=0} = r\omega \quad (4)$$

Furthermore, given the transportation time *T* and distance *d*, one should therefore choose *r* and ω such that $V_{transportation} = \frac{d}{T}$. Note that to change the motion direction, the direction of ω would change. It can be shown that the wave particles at the wave crests move at a different direction compared to the wave particles at the wave troughs ($V_{crest} = r\omega$ and $V_{trough} = -r\omega$) and we will get the maximum transportation speed if the object is kept at the wave crests.



(A)



(B)

Figure 3.2. Schematics of a traveling wave. (A) A traveling wave that consists of individual wave particles, shown as yellow circles; where each particle follows an elliptical trajectory in the clockwise direction to move the rectangular object to the right. (B) Details of the elliptical trajectory of the particle, adapted from [71].

3.3.1.2 MOVEMENT SMOOTHNESS ANALYSIS

One goal of this study was to investigate how different wave parameters affect movement smoothness as the object traverses along the wave. To analyze this, we first need to define smoothness quantitatively. In the transportation engineering literature, pavement smoothness is a measure of the level of comfort experienced by the traveling public while riding over a pavement surface [137]. There are a couple of different indices for measuring surface roughness [137]. One frequently used metric is called the International Roughness Index (IRI), which is defined as the accumulated suspension strokes over the traveled distance during the travel time [137]. Inspired by the IRI index definition, we defined movement smoothness *s* as the inverse of the average of the object vertical displacement over a travelled distance equal to one wavelength which is given by

$$s = \left(\frac{average\ (\Delta y_{object})}{\lambda}\right)^{-1} \quad (5)$$

To calculate smoothness, we first need to analytically derive object vertical displacement profile as a function of time ($\Delta y_{object}\ (t)$) as the following. At time $t = 0$, the object is supported by the wave particles at the wave crest such as P_1 in Figure 3.2(A) where $y_{object}(0) = R$ and the y coordinate of P_1 is given by Equation (6). The object is moved downwards and at time $t = t_1$, the object loses contact with P_1 and is supported by the next set of particles, such as P_2, which then support and move the object upwards. The y coordinate of P_2 is given by Equation (7), and θ_0 is the phase difference between adjacent particles. The same motion occurs periodically and $y_{object}(t)$ would be a sinusoidal signal. Therefore, to get the vertical displacement of the object $y_{object}(t)$, we set $y_{P_2} = y_{P_1}$ at $t = t_1$ and we will have:

$$y_{P_1}(t) = Rcos(\omega t) \quad (6)$$

$$y_{P_2}(t) = Rcos(\omega t - \theta_0) \quad (7)$$

$$At\ t = t_1 : y_{P_2} = y_{P_1} \rightarrow\ 2N\pi - (\omega t_1 -\ \theta_0) = \omega t_1 \quad (8)$$

where periodicity is observed with $N \in \mathbb{Z}^+$. Setting $N = 0$, we will get:

$$t_1 = \frac{\theta_0}{2\omega} \quad (9)$$

Thus, $y_{object}(t_1) = y_{P_1}(t_1) = Rcos(\frac{\theta_0}{2})$ and the amplitude at any time is $y_{object}(t) = R - Rcos\left(\frac{\theta_0}{2}\right)$. As we will show in section 3.3.2, the period of $y_{object}(t)$ signal is $\frac{\theta_0}{\omega}$. The trajectory of $y_{object}(t)$ is plotted in Figure 3.6 and therefore, can be given by

$$y_{object}(t) = R + R\left(1 - \cos\left(\frac{\theta_0}{2}\right)\right)\left(\left|\cos\frac{\omega\pi t}{\theta_0}\right| - 1\right) \tag{10}$$

Using Equation (10), to calculate $average(\Delta y_{object})$, we assume that the object moves for one wavelength during *T*. Therefore, we will have:

$$average\left(\Delta y_{object}\right) = \frac{\int_0^T (R - y_{object})dt}{T} \tag{11}$$

To calculate smoothness, we use the fact that the object moves at a constant transportation speed of $r\omega$ for a time T which results in a distance equal to λ and given by

$$\lambda = r\omega T \tag{12}$$

Using Equations (5), and (10)-(12), we will have the following formula for movement smoothness which implies that smoothness is a function of *r*, *R*, λ, and θ_0 (Equation (14)).

$$s = \left|\frac{R}{r}\left(1 - \cos\left(\frac{\theta_0}{2}\right)\right)\left(-\left(\frac{r}{\lambda}\right)^2\left(\frac{\theta_0}{\pi}\right)\left(-\sin\left(\frac{\lambda\pi}{r\theta_0}\right) + 2\right) + \frac{r}{\lambda}\right)\right|^{-1} \tag{14}$$

Smoothness, *s*, can be plotted as a function $\frac{r}{R}$, $\frac{r}{\lambda}$, and θ_0, which are all dimensionless quantities (Figures 3.3-3.5). Smoothness vs. $\frac{r}{R}$ plot indicates that to maximize movement smoothness, the ratio $\frac{r}{R}$ should be maximized which implies that r should increase while R should decrease (Figure 2.3). Additionally, from the smoothness vs. $\frac{r}{\lambda}$ plot, it is observed that to maximize smoothness, $\frac{r}{\lambda}$ should be maximized which implies that r should increase while λ should decrease meaning that the wave crests should be closer to each other so that more crests support the body (Figure 3.4). Lastly, to maximize movement smoothness, θ_0 should be minimized which implies that the number of wave-generating actuators should be increased (Figure 3.5). However, one should also not that increasing the number of actuators means that we should have a more complex design and control architecture Therefore, there is a tradeoff between smoothness and θ_0.

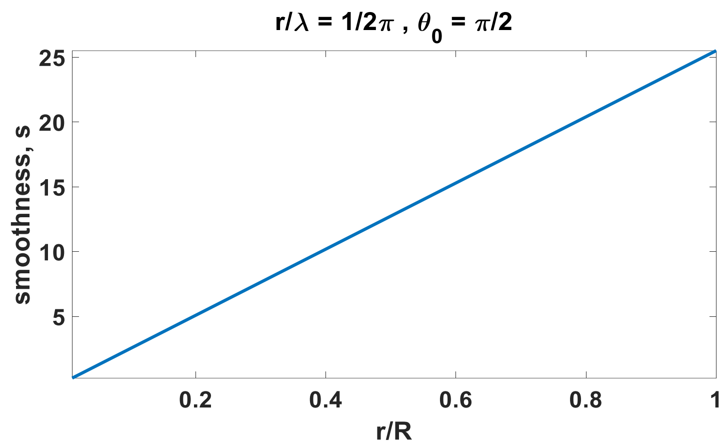


Figure 3.3. Smoothness as a function of $\frac{r}{R}$ for a fixed phase difference of $\theta_0 = \frac{\pi}{2}$ and $\frac{r}{\lambda} = 0.1$.

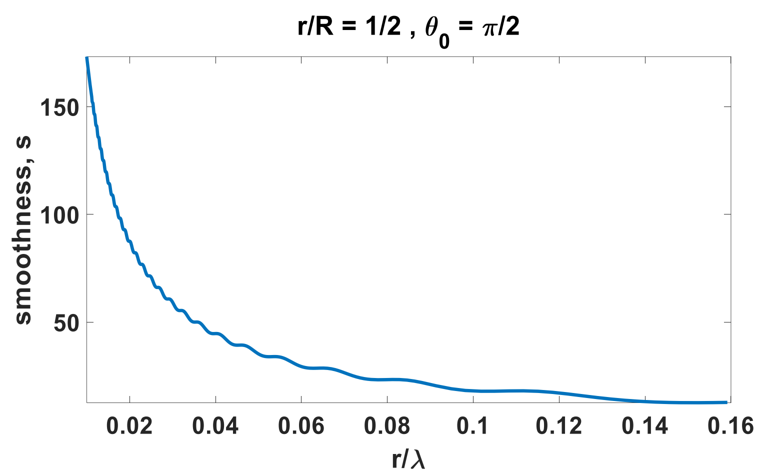


Figure 3.4. Smoothness as a function of $\frac{r}{\lambda}$ for a fixed phase difference of $\theta_0 = \frac{\pi}{2}$ and $\frac{r}{R} = 0.5$.

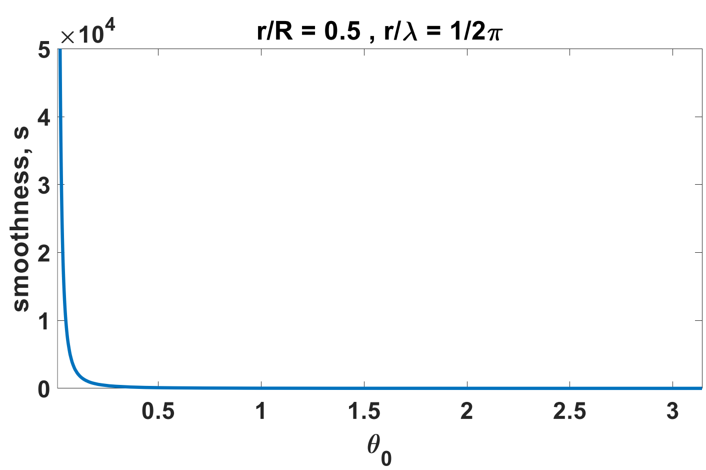


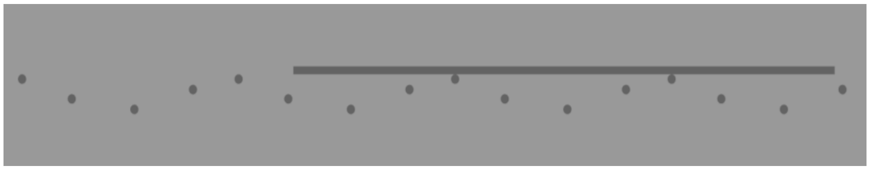
Figure 3.5. Smoothness as a function of phase difference θ_0 between adjacent actuators for fixed ratios of $\frac{r}{R} = 0.5$ and $\frac{r}{\lambda} = 1/2\pi$.

Additionally, to ensure no tilting motion, the object must be supported by at least two crests at all times. Otherwise, the object loses stability (Figure 3.6(B)). Therefore, the maximum upper bound for the wavelength is $\lambda < L/2$. As theoretically proved in [29], the lower bound for the wavelength should exceed the critical value of $2\pi r$. Otherwise, the wave contour would wrap over itself, which is not physically achievable in real-world applications. Therefore, the wavelength to prevent tilting of a rigid object that is riding the crests of multiple waves should fall within this range, $2\pi r < \lambda < L/2$.

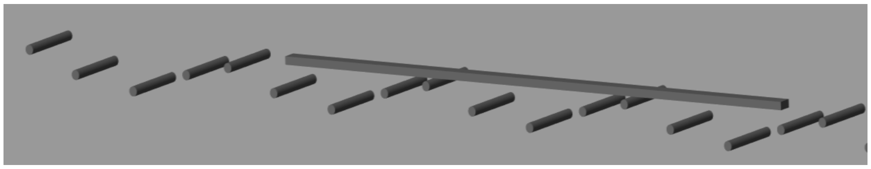
3.3.2 SIMULATION OF A TRAVELING WAVE

To better understand the effect of each wave parameter on the transportation speed and movement smoothness, we simulated the traveling wave in the MATLAB Simscape Multibody environment (MATLAB 2021a) (Figure 3.6). Each wave particle was modeled as a solid cylindrical element block connected to a Cartesian joint block with two translational degrees of freedom (DOFs) in the x and y directions. To change the wavelength, the spacing between wave particles was adjusted. Furthermore, to change the number of wave particles, θ_0 was changed. Two sinusoidal signals were used to actuate the translational DOFs $x_p$and y_p given by Equations (1) and (2). The object was modeled as a solid brick element with the dimensions L, H, and W in the x, y, and z directions, respectively, and connected to a 6 DOF joint block. Furthermore, to model the contact between the object and wave particles, a spatial contact force block was used. (For more details, please refer to section A2 in the Appendix.)

The simulated object vertical displacement $y_{object}(t)$ as a function of time is shown in Figure 3.7, where it is noted that the contact between the object and each set of wave actuators that are supporting it lasts for $\Delta t_{contact} = \frac{\theta_0}{\omega}$.



(A)



(B)

Figure 3.6. Simulated traveling wave and the transported object. (A) Front view. (B) Isometric view.

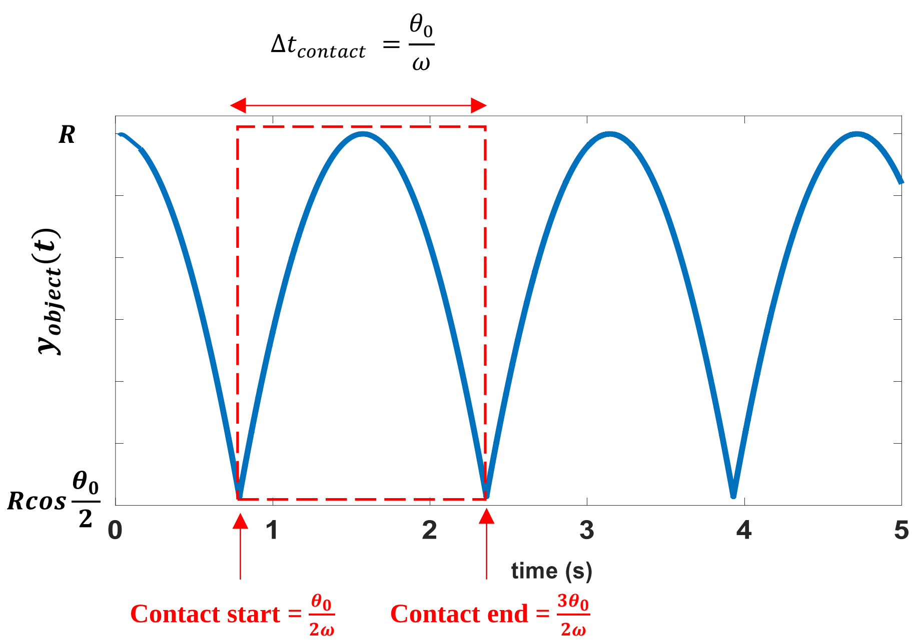


Figure 3.7. Simulated object vertical displacement as a function of time. A single contact region is shown as an example. The object is first supported at the wave crest, then moves downwards, and detaches from the wave particle at the bottom of the plot. The object is then supported by the next wave particle and moves upwards. The same periodic motion happens over time. The contact between an individual wave particle and the object lasts for $\Delta t_{contact} = \frac{\theta_0}{\omega}$ (which implies the period of object movement). $\omega = 1\ rad/s$ and $\theta_0 = \frac{\pi}{2}$.

3.4 REQUIREMENTS FOR MOVING AN ELASTIC OBJECT USING TRAVELING WAVES

As discussed earlier in section 3.3, the goal is to keep the body at the wave crests as much as possible to increase both transportation speed and movement smoothness. The analyses in sections 3.3.1.1 and 3.3.1.2 were based on a rigid body assumption. However, an elastic object such as the human body might deform to the wave shape. As mentioned in section 3.3.1, at each fixed moment, different wave particles move at different rotational velocities. If we have a rigid object, the object will only be in contact with the wave particles that have the same phase angle (i.e., the phase difference is $2N\pi$ where $N = 0,1,2, \ldots$). However, in the case of a flexible object, different parts of the object might be in contact with the wave particles with different phase angles (e.g., some parts are in contact with the wave crests while other touch the particles at the wave troughs). Therefore, different parts of a deformable body would move at different velocities and in different directions, which is not desirable. In this section, we will investigate the additional requirements that we should have for transferring an elastic body such as a human body. We assume that there is an elastic or deformable interface layer between the body and the wave particles; then the layer is subjected to the body weight and might deflect and conform to the wave shape (Figure 3.8). We would like to understand what the minimum required stiffness of the interface layer should be so that it only contacts the wave particles near the wave crests.

Let the interface layer be a rectangular plate of the thickness *t*, Young's modulus *E*, and Poisson's ratio ν (Figure 3.8). In plate theory, the plate stiffness *K* is given by Equation (15).

$$K = \frac{Et^3}{12(1-\nu)} \tag{15}$$

Initially, the plate is supported by a set of wave particles such as P_1 at the wave crests across its length and is loaded under body weight. The deflected interface layer is also shown in Figure. 3.8.

We will only consider part of the plate that is between the two wave particles at the crests where the plate's lengths are a and b in the x and z directions, respectively. We assume that the plate thickness is much smaller compared to the length a, and the plate stiffness K is the same throughout the plate. The idea is to minimize the maximum deflection of the plate δ_{max} such that it is less than the vertical distance between particles P_1 and P_2 to avoid its contact with P_2, since P_2 particles have a phase angle different from P_1 particles.

The maximum deflection of a rectangular plate under uniform load and fixed-fixed boundary conditions at the end edges is given by Equation (16).

$$\delta_{max} = 0.0026 \frac{12(1-\nu^2)Pb^4}{Et^3\left[1.056\left(\frac{b}{a}\right)^5 + 1\right]} \tag{16}$$

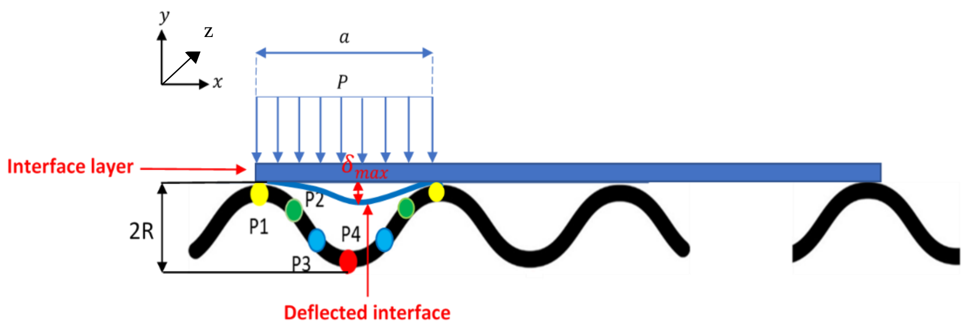


Figure 3.8. The interface layer is supported at two ends by two wave particles shown in yellow circle at the wave crests and is uniformly loaded and deflected as a result of the applied distributed load P. Note that we are only showing the wave and the interface layer in the x-y plane of Figure. 3.1.

Combining Equations (15) and (16), the maximum deflection can be written as

$$\delta_{max} = 0.0026 \frac{Pb^4}{K\left[1.056\left(\frac{b}{a}\right)^5 + 1\right]} \tag{17}$$

where in our case, $a = \lambda$.

To calculate δ_{max}, we need to estimate the applied load P which implies that we need to estimate the weight distribution of each body part. We divide the body into four parts: head, trunk, hip, and the legs. For each body part, we use the anthropometric data given in [33] to calculate the weight distributions. Since we should only consider the worst-case scenario (maximum δ_{max}) which happens when we have the highest load distribution on the plate, then we need to know what body part has the highest weight. The calculation found that the trunk has the highest weight distribution given by

$$P_{trunk} = 8.5\frac{W}{h^2} \tag{18}$$

where W and h are the human body weight and height, respectively. Therefore, the worst-case scenario is when the portion of the plate which is supported by the two wave particles at the crests is loaded uniformly by the trunk weight (which has the highest load distribution).

In the next step, we need to set an upper bound for δ_{max}. The vertical distance between P_1 and P_2 is given by

$$\Delta y = \frac{2R}{(\frac{\pi}{\theta_0})} \tag{19}$$

where R is the magnitude of the major axis of the elliptical trajectory (or equivalently, the wave amplitude) and θ_0 is the phase difference between two adjacent wave particles. $\delta_{max} < \Delta y$ is not a sufficient upper bound condition for δ_{max}. This is because the wave particles are moving dynamically and their distance changes as a function of time. Therefore, we adjust the equation to $\delta_{max} < \alpha\Delta y$, where $0 < \alpha \ll 1$. This implies that the designer can pick the design coefficient α to bound δ_{max} to only a small fraction of Δy to ensure that the object does not touch P_2. Thus, we will have

$$\delta_{max} < \alpha\frac{2R}{(\frac{\pi}{\theta_0})} \tag{20}$$

Note that smaller values of α imply that we need a stiffer plate since we are setting a very small upper bound for δ_{max}. Combining Equations (17) and (20), we can now propose that the plate stiffness should satisfy Equation (21).

$$K > 0.0026 \frac{Pb^4}{\left[1.056\left(\frac{b}{\lambda}\right)^5 + 1\right]} \frac{(\frac{\pi}{\theta_0})}{2R\alpha} \tag{21}$$

Note that in the case of transferring a human body, $P = P_{trunk}$ and is given by Equation 18. Therefore, the minimum required stiffness of the plate should be: $K_{min} = 0.0026 \frac{P_{trunk}b^4}{\left[1.056\left(\frac{b}{\lambda}\right)^5 + 1\right]} \frac{(\frac{\pi}{\theta_0})}{2R\alpha}$.

3.5 RECOMMENDED DESIGN GUIDELINES

Based on the above analyses, the following design guidelines are proposed for moving a body using traveling waves based on desired transportation speed of the body, smoothness of the motion, and stiffness of the interface layer between the body and the wave (Table 3.1).

Table 3.1. Summary of design requirements for moving a body using traveling waves

	Transportation speed	**Movement smoothness**	**Elastic object transportation requirements**
Equation	$V_{transportation} = r\omega$	$s = \left\| \frac{R}{r}\left(1 - \cos\left(\frac{\theta_0}{2}\right)\right)\left(-\left(\frac{r}{\lambda}\right)^2\left(\frac{\theta_0}{\pi}\right)\left(-\sin\left(\frac{\lambda\pi}{r\theta_0}\right) + 2\right) + \frac{r}{\lambda}\right)\right\|^{-1}$	$K > 0.0026 \frac{Pb^4}{\left[1.056\left(\frac{b}{\lambda}\right)^5 + 1\right]^{\frac{(\frac{\pi}{\theta_0})}{2R\alpha}}}$
Guideline(s)	Given a desired transportation speed of $V_{desired}$, r and ω should be chosen such that: $V_{desired} = r\omega$	To increase movement smoothness: (1) r should increase. (2) R (or the wave amplitude) should decrease. (3) λ should decrease. (4) θ_0 should decrease (or equivalently the number of wave particles should increase). (5) To ensure a stable motion, we should have: $2\pi r < \lambda < L/2$ where L is the object's length.	The stiffness of the interface layer between the body and the wave particles K should satisfy the above equation.
Definitions	r: Magnitude of the minor axis of the elliptical trajectory ω: Wave frequency $V_{transportation}$: Transportation speed $V_{desired}$: Desired transportation speed	s: Movement smoothness r: Magnitude of the minor axis of the elliptical trajectory R: Magnitude of the major axis of the elliptical trajectory θ_0: Phase difference between two adjacent wave-generating actuators λ: Wavelength L: object's length	P: Magnitude of the pressure on the interface layer b: Width of the interface layer R: Magnitude of the major axis of the elliptical trajectory θ_0: Phase difference between two adjacent wave-generating actuators α: Design coefficient ($0 < \alpha \ll 1$) K: Interface layer stiffness λ: Wavelength

3.6 DISCUSSION

This study investigated the effect of different wave parameters on transportation speed and movement smoothness through kinematic analysis and simulation of a traveling wave. Furthermore, the study explored the additional requirements that need to be satisfied with regards to the minimum stiffness of the interface layer between the human body and the wave actuators. The kinematic analysis results indicated that transportation speed is linearly proportional to r, the minor axis of the elliptical wave-particle motion, and ω, which is the angular velocity of the wave particle (and also wave frequency) as given by Equation (4), and has its maximum value at the wave crests. Furthermore, movement smoothness is a function of r, R, λ, and θ_0 (or equivalently, the wave particles movement pattern, wavelength, and the number of wave particles), as shown in Equation (14). To increase movement smoothness, the ratio $\frac{r}{R}$ should increase, which in its extreme limits (i.e., $\frac{r}{R} \to \infty$) boils down to a purely translational motion such as that of a conveyor belt (Figure 3.3). However, a single conveyor belt can only move the object in one direction, and it fails to provide two-dimensional motion. A two-dimensional conveyor belt could be designed for this purpose; yet it may be challenging to obtain independently controlled two-dimensional planar motion from a system of conveyor belts.

Furthermore, Equation (14) suggests that to maximize smoothness, the ratio $\frac{r}{\lambda}$ should be maximized which implies that r should increase while the wavelength λ should decrease (Figure 3.4). This makes sense since as the wavelength is decreased, the wave crests will be closer to each other and thus, more wave crests will support the object which will increase smoothness. However, as analytically proved in [86], the wavelength should exceed the critical value of $2\pi r$ which implies that $\frac{r}{\lambda}$ should be less than $\frac{1}{2\pi}$; otherwise, the wave contour would wrap over itself which is not physically feasible in practice. Meanwhile, as explained in section 3.3.2 and shown in Figure 3.6, the wavelength should be less than half of the object length to ensure a stable motion.

Additionally, to increase smoothness, the phase difference θ_0 between adjacent particles should decrease which implies that the number of wave particles should increase (Figure 3.5). However, one should note that to create a traveling wave in practice using discrete actuators, we have a constraint on the allowable spacing between adjacent actuators. Increasing the number of wave particles implies a more complex actuation system design and control architecture.

Therefore, there is a tradeoff between movement smoothness and complexity of the system design and control.

Regarding the minimum required stiffness of the interface layer between the body and the wave actuators in case of transporting elastic bodies such as the human body, Equation (21) suggests that the wavelength, wave amplitude (which is the same as R), the phase difference between adjacent actuators (or equivalently, the number of wave-generating actuators), and the design factor α will determine the minimum required stiffness of the interface layer. Increasing the wave amplitude (or R) and the phase difference between actuators, and decreasing the wavelength will result in a smaller lower bound for the minimum needed stiffness which implies that we will have more flexibility on choosing the material for the interface layer (i.e., we could choose a less rigid layer).

This study has a few limitations. One limitation is that we only focused on an elliptical trajectory for the wave particles to create the wave since this trajectory is observed in natural waves such as water waves. However, in general, to move a body using a wave, we do not necessarily need an elliptical trajectory and as far as the wave particles move periodically along any given closed-loop trajectory, we can create the wave. Given this, one might be able to create the closed-loop trajectory using only translational actuators rather than rotational actuators and generally, creating a translational motion is easier than a rotational motion. Therefore, this way of creating a wave might simplify the actuation design. The other limitation is that when considering the requirements for moving an elastic body such as the human body, we are simply assuming that the wave-generating actuators are rigid. However, if the wave-generating actuation mechanism itself is compliant, one might need to perform further analysis as the actuators might also deform. For the case of human transfer specifically, additional considerations with respect to the human body comfort as well as the required actuation forces must also be established.

Future research direction includes determining the actuation forces that are needed to move the body. Additionally, future research may include the fabrication and experimental validation of a small prototype of a surface traveling wave-generating mechanism based on the study results for moving an object as a proof-of-concept.

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 [46]. Future work may include the design and fabrication of a small bed prototype with an embedded traveling wave generating mechanism where a variable-stiffness mattress based on the idea of particle jamming could be placed on top of the bed surface. In case of transferring the human body, the stiffness of the mattress could be changed to meet the minimum required stiffness for transferring elastic objects as discussed in section (3.4). When the human body is not supposed to be transferred and is only lying on the mattress, the stiffness could be changed to meet the human body comfort requirements.

3.7 CONCLUSIONS

This study investigated the design requirements for moving a human body using traveling waves. In particular, through kinematic analysis and simulation of a traveling wave, the study investigated how different wave parameters such as the wavelength, wave amplitude, wave frequency, and the number of wave particles or wave-generating actuators would affect transportation speed and movement smoothness, and proposed a set of design requirements for moving a body using traveling waves. Additional requirements with regards to the minimum stiffness of the interface layer between the body and wave particles were also established in case of moving an elastic object such as the human body.

The proposed design framework can help with the design and fabrication of traveling wave-generating actuation systems to transfer objects. Potential applications include integrating a surface wave-generating transfer device as part of a bed mattress for transferring immobile patients anywhere on the mattress plane using two-dimensional surface waves to remove the burden of physical patient transfer from caregivers.

CHAPTER 4: CONCLUSIONS

In Chapter 1, we gave a brief overview and background of current technologies for mitigation of pressure ulcer development in terms of pressure-relieving and repositioning devices and devices to move or transfer patients with a limited body movement ability in bed. The concept of using traveling waves for human transfer was also investigated in the larger context of object transportation and manipulation using soft peristaltic tables, and the related work was reviewed. Our review of proposed peristaltic tables in the literature suggested that most work in this area relies on experimental approaches where a peristaltic table has been built and tested empirically. Additionally, there are very few papers that have proposed design requirements for moving an object using traveling waves independent from the type of the actuators.

In Chapter 2, we investigated the existing technologies more comprehensively in terms of their mechanical design, actuation methods, sensing technologies, control architectures, and device autonomy. The devices were classified into four main categories namely pressure-relieving, repositioning, transfer, and combined solutions. Each category was further categorized into a set of subcategories and their limitations were identified. Additionally, potential design opportunities were proposed and discussed to address the gaps in the literature.

In Chapter 3, a second study was conducted to present a more comprehensive set of actuator-agnostic design guidelines for moving a human body using traveling waves. More specifically, the objective was to better understand how different wave parameters such as the wavelength, wave amplitude, wave frequency, and the movement pattern of the wave-generating actuators would d change transportation speed and movement smoothness. Through a kinematic analysis and simulation of a traveling wave, the study suggested that transportation speed is linearly proportional to the wave speed ω and the magnitude of the minor axis of the elliptical trajectory r that each wave-generating actuator follows. Therefore, given a desired transportation speed $V_{desired}$, one needs to choose ω and r such that $V_{desired} = r\omega$. Additionally, movement smoothness s is a function of the magnitude of the minor and major axes of the elliptical trajectory, namely r and R, the wavelength λ, and the phase difference between adjacent actuators θ_0 (or equivalently, the number of wave-generating actuators). To maximize smoothness, r should be maximized while R should be minimized which in its extreme results in a purely translational motion such as that of a conveyor belt. However, a single conveyor belt can only move the object in one direction, and it fails to provide planar body motion and transfer. A two-dimensional conveyor belt could be designed for this purpose; however, it may be challenging to obtain independently controlled two-dimensional planar motion from a system of conveyor belts.

Furthermore, to increase movement smoothness s, the wavelength λ should be decreased which implies that more wave crests are needed to support the object. Besides, decreasing the phase difference θ_0 between adjacent actuators (which also implies increasing the number of wave-generating actuators) will result in a larger movement smoothness. However, increasing the number of wave actuators means a more complex actuation system design and control architecture. Therefore, there is a tradeoff between movement smoothness and complexity of the system design and control.

Lastly, the study in Chapter 3 explored the additional design requirements that are needed to move an elastic body such as a human body. The study suggested that the minimum required stiffness of the interface layer between the human body and the wave particles depends on R, λ, and θ_0. In particular, increasing R and decreasing λ and θ_0 will give the designer the flexibility to choose a less stiff material for the interface layer.

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APENDIX A: MATLAB CODE FOR MODELING THE TRAVELING WAVE

```
%% The following code specifies the wave parameters.
%% All the dimensions are in unit length.

%% Transverse bars dimensions (transverse bars represent wave particles)

%% bar length
L_bar = 5;

%% bar radius
R_bar = 0.3;

%% Wavelength is equal to the distance between two particles at the wave troughs or wave crests:
lambda = 20;


%% Wave frequency
omega = 1; %%rad/s

%% Wave amplitude
amp = 1;

%% Ellipse major axis length
R = 1;

%% Ellipse major axis length
r = 0.5;

%% phase difference between two adjacent particles
theta_0 = pi/2;

%% d is the spacing between two adjacent actuators.
d = lambda/2/(pi/theta_0);

%% Object specifications:
L_object = 33; %% should be at least twice the wavelength.
W_object = 0.5;
H_object = 1;
object_density = 7800; %%kg/m^3

%% Rigid object initial position
x_object = 25;
y_object = -1.8;
z_object = -1;



%% Contact parameters
%% Normal force parameters
```

```
stiffness = object_density*L_object*W_object*H_object/0.001;

%% for stiffness use this eqn: k=F/d=mg/d where d is the penetration depth. k=object_mass*g/d
damping = stiffness/10;
transition_region_width = 10^-4;

%% Frictional force parameters
mu_s = 0.5; %% static friction coefficient
mu_k = 0.3; %% kinetic friction coefficient
critical_velocity = 10^-3;
```

APENDIX B: SIMULINK BLOCK DIAGRAM FOR SIMULATING THE TRAVELING WAVE AND THE CONTACT BETWEEN THE OBJECT AND THE TRAVELING WAVE

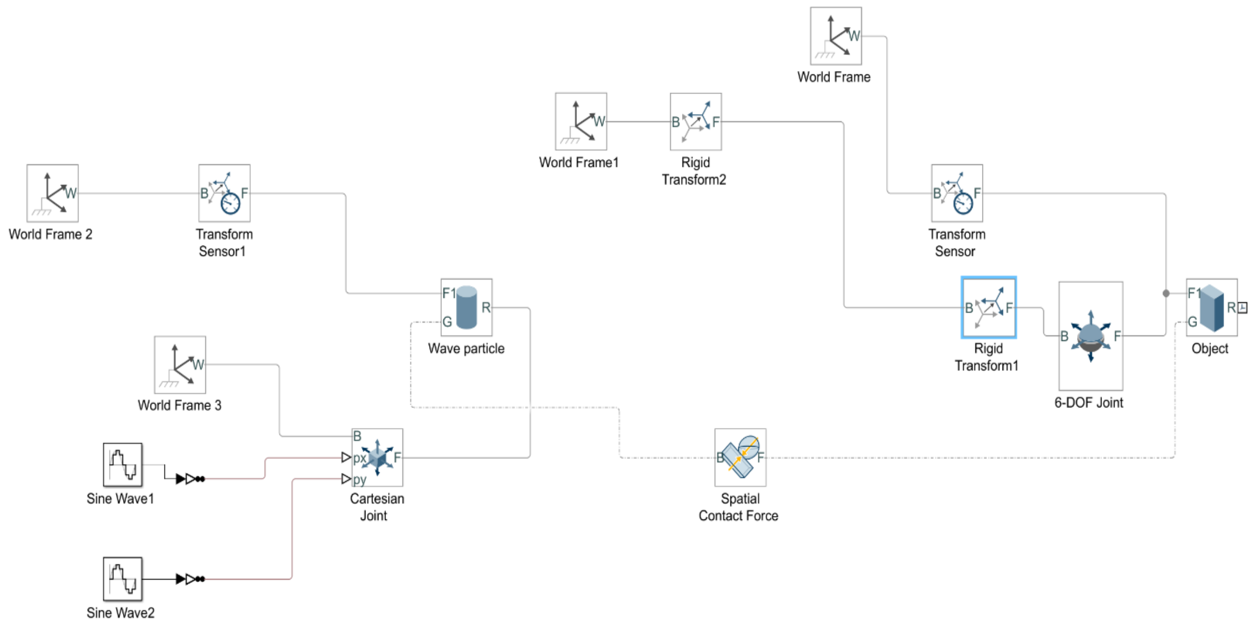

Figure A1. Block diagram for simulating the traveling wave and the contact between the object and one traveling-wave generating actuator. As noted in section 2.3.2, each wave particle was modeled as a solid cylindrical element block (named as Wave particle in the figure) connected to a Cartesian joint block with two translational degrees of freedom (DOFs) in the x and y directions. Two sinusoidal signals were used to actuate the translational DOFs x_p and y_p given by Equations (1) and (2). The object was modeled as a solid brick element with the dimensions L, H, and W in the x, y, and z directions, respectively, and connected to a 6-DOF joint block. Furthermore, the spatial contact force block was used to model the contact between the object and wave particles, a. To change the wavelength, the spacing between wave particles was adjusted in the MATLAB code in section A1. Additionally, to change the number of wave particles, θ_0 was changed in the MATLAB code in the section A1.