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DESIGN GUIDELINES FOR MOVING A HUMAN BODY ON A BED USING TRAVELING WAVES

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ABSTRACT

Inspired by natural waves such as water waves that can carry objects, this study presents design guidelines for moving a human body using traveling waves created on the surface of a bed. Particularly, through kinematic analysis and simulation of a traveling wave, the study explores various parameters, such as the wave's frequency, wavelength, amplitude, number of wave-generating actuators and their movement pattern under the body. The study also investigates how these parameters affect human transportation speed and movement smoothness. The study results suggest that transportation speed is linearly proportional to the wave frequency. Additionally, to increase movement smoothness, the wave amplitude should be reduced while the number of actuators should be maximized. However, there is a tradeoff between the number of actuators that can be used and the complexity of the system's design and control.

Keywords: Patient transfer, patient repositioning, caregiver injury

1. INTRODUCTION

Patients with limited personal body movement ability need assistance from caregivers for transfers and repositioning when lying on a bed. For example, they may need to be moved to the edge of the mattress for transfer from the bed to a wheelchair, or they may need to be readjusted on the mattress if they slide 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 [1]. Manually moving a patient is a physically demanding task that can lead to musculoskeletal disorders for the caregivers and skin abrasion for patients [1]. To address these issues, alternative devices for patient transfer have been proposed. Commercial technologies include mechanical lifts [2] or conveyor belts [3] that reduce the physical effort of the caregiver. Research-level devices include humanoid robots that can lift and move a person [4], weight-supporting mechanical arms that can hold a person from the waist and lift them [5], and bed-to-wheelchair converting devices where part of the bed is transformed into a wheelchair for patient transfer [6]. 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. Furthermore, 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 [7] created a partial bed surface where a series of slider-crank mechanisms were used to create a wave to move a body to the edge of the bed. Additionally, they proposed a set of design guidelines for using these surface waves to move a body. The idea of moving patients via traveling waves may be able 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.

The goal of this study was to build upon the prior work of Spano and Asada [7] 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 parameters such as the wavelength, frequency, amplitude, number of actuators used to generate the wave, 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 (Fig. 1). Furthermore, these design requirements are intended to be agnostic to actuator type.

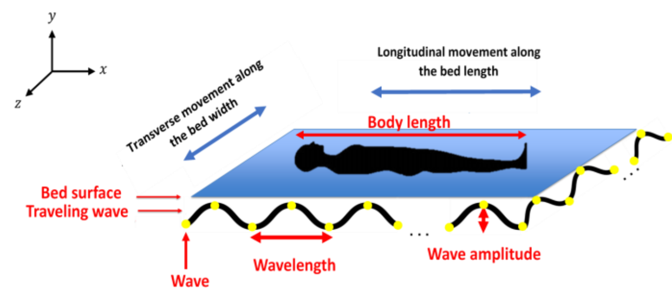


FIGURE 1: Schematic of moving a human body on the surface of a bed using traveling waves in two dimensions.

2. MATERIALS AND METHODS

2.1 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.

2.1.1 Transportation speed analysis

The problem is defined as the following, as was proposed in [7]. We would like to move an object of mass M and with length L (Fig. 2A). 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 a distance u from the origin, with minor and major axes of r and R, respectively (Fig. 2B) (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, moves downward, detaches from the object, 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. (In Fig. 2A, 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

$$x_p(u,t) = u + r \sin\theta(u,t) \tag{1}$$

$$y_p(u,t) = R\cos\theta(u,t) \tag{2}$$

where $\theta(u,t)$ is shown in Fig. 2B and is given by

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

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)).

$$V_{transportation} = \frac{\partial x_p}{\partial t}\Big|_{\theta=0} = r\omega \tag{4}$$

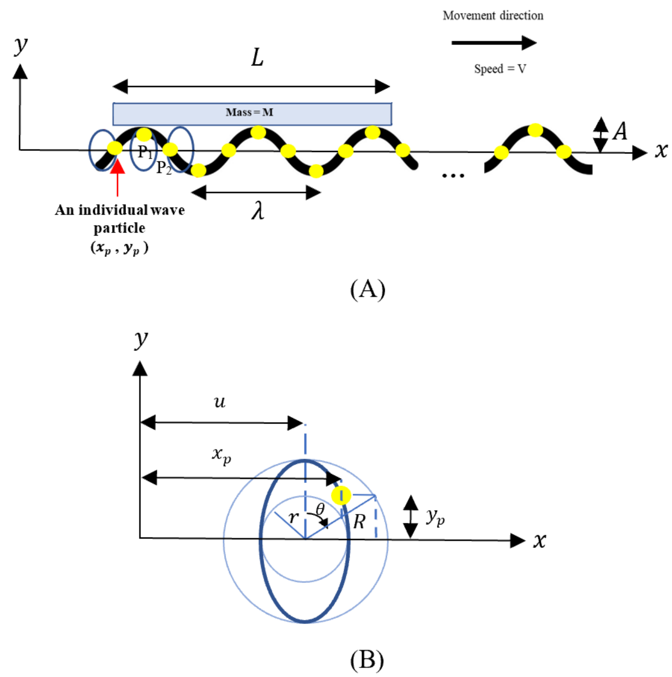


FIGURE 2: Schematics of a traveling wave. (A) A traveling wave that consists of individual wave particles, shown as yellow circles; where each particle follows an elliptical trajectory in the clockwise direction to move the rectangular object to the right. (B) Details of the elliptical trajectory of the particle, adapted from [7].

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 the maximum transportation speed occurs if the object is kept at the wave crests.

2.1.2 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 needed 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 [8]. There are a couple of different indices for measuring surface roughness [8]. 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 [8]. Therefore, we defined movement smoothness *s* as the inverse of the IRI index which is given by:

$$s = \left[\frac{\int_0^T |\dot{y}_{object}| dt}{d}\right]^{-1} \quad (5)$$

The trajectory of $y_{object}(t)$ was achieved based on the simulation results presented in section 2.2 and given by

$$y_{object}(t) = R - R\left(1 - \cos\left(\frac{\theta_0}{2}\right)\right)\left(\left|\cos\frac{\pi\omega t}{\theta_0}\right| - 1\right) \quad (6)$$

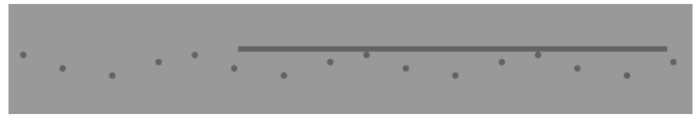
Using Equations (5) and (6), movement smoothness *s* was analytically derived as

$$s = \left[\frac{1}{d}\int_0^T \frac{\pi R\omega}{\theta_0}\left(1 - \cos\frac{\theta_0}{2}\right)\left|\sin\frac{\omega\pi t}{\theta_0}\right| dt\right]^{-1} \quad (7)$$

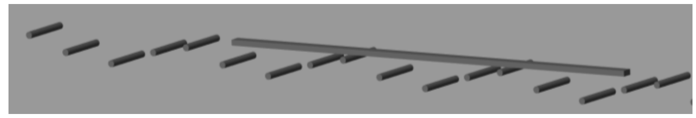
where r and R are the lengths of the minor and major axes of the elliptical trajectory of each wave particle, θ_0 is the phase difference between two adjacent wave particles, and ω is the frequency of the cyclic motion. Also, given Equation (4), note that $d = r\omega T$, therefore, r will also appear in the smoothness equation.

2.2 Simulation of a traveling wave

To better understand the effect of each wave parameter on the transportation speed and smoothness, we simulated the traveling wave in MATLAB Simscape Multibody environment (MATLAB 2021a) (Fig. 3). 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.



(A)



(B)

FIGURE 3: Simulated traveling wave and the transported object. (A) Front view. (B) Isometric view.

3. DISCUSSION

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 as given by Equation (4), and has its maximum value at the wave crests. Furthermore, movement smoothness is a function of *r*, *R*, and θ_0 (or equivalently, the movement kinematics and number of individual wave particles), as shown in Equation (7). To increase movement smoothness, *R* should decrease whereas *r* should increase, which in its extreme limits boil down to 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 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.

Additionally, to increase smoothness, the number of wave particles should increase (or equivalently, the phase difference between adjacent actuators should decrease). However, 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.

4. LIMITATIONS AND FUTURE WORK

One limitation of this study is that we focused solely on an elliptical trajectory for the wave particles to create the wave since this trajectory is observed in naturally occurring waves, such as water waves. However, in general, to move a body using a wave, the wave particles could exhibit periodic motion along any close-loop trajectory, with the elliptical trajectory as a specialized case. The type of trajectory will determine the motion requirement of the actuators, which could be either translational, rotational or their combination. We may be thus inclined to choose a trajectory that simplifies the design of the actuators.

In the future, we will address a number of additional design guidelines. We will explore the additional design guidelines needed to move an elastic object such as the human body with regards to the minimum required stiffness of the interface between the human body and the wave particles. Additional considerations with respect to the human body comfort will be investigated. Understanding the actuation forces to move the body will also be considered.

5. CONCLUSION

This study investigated a preliminary set of design guidelines for moving a human body on a bed surface using traveling waves. In particular, through kinematic analysis and simulation of a traveling wave, the study investigated how different wave parameters affect transportation speed and movement smoothness. The proposed design framework can guide the development of actuation systems to physically realize a traveling wave that can move humans on a bed.

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