A Versatile Emulator for Haptic Communication to Alter Human Gait Parameters

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***Abstract*— Robotic devices that interact with humans at the hands through haptic communication instead of mechanical power transmission represent an intuitive way to assist persons with physical disabilities and teach movement skills. Principles of human-human haptic communication during walking could inspire novel robot controllers capable of altering specific spatiotemporal gait parameters, not just walking speed. However, we know little about how hand interactions affect gait parameters, as existing hand-contact robots have several performance limitations that hinder rapid testing of different controllers and parameters. Here we present the design and validation of Slidey, a novel robotic testbed capable of emulating diverse hand interactions to alter human gait parameters. A lightweight, instrumented linear stage translating on a > 5 m long track, Slidey allows overground walking at speeds ≤ 2.4 m/s; high-fidelity current and position control at > 500 Hz and ~ 6 Hz, respectively; and stable rendering of a range of admittances (mass ≤ 10 kg, damping ≤ 20 N/(m/s)). We show proof-of-concept that Slidey has adequate functionality to target changes in step length or step frequency. Slidey can act as a high-fidelity robotic emulator to rapidly investigate, evaluate, and personalize robot controllers to alter gait through haptic communication at the hand.**

I. Introduction

Haptic communication – the use of touch for information transfer as opposed to mechanical power transmission [1] - at the hand represents a novel and intuitive approach to aid and alter human walking. This approach avoids exerting large loads on the person's body and does not require donning or doffing (as opposed to wearable "exoskeletons"). The potential for subtle hand interactions to alter walking without explicit instructions are demonstrated in activities such as two people holding hands while walking or partner dancing. Studies in haptic communication have demonstrated that human pairs use low-force (2 N [2] to 30 N [3]) hand interactions during walking to synchronize gait phase [2], [4], signal transitions [3], and aid balance [5].

Physical human-robot interactions (pHRI) have the potential to apply haptic communication principles used by humans to several walking applications, such as assistive technology for persons with visual or walking impairments and teaching movement skills (e.g. dance or sports activities) to persons with or without physical disabilities. However, to investigate and apply haptic communication principles, pHRI devices must be capable of emulating a wide range of human hand behaviors during walking.

A variety of custom, one-off hand-contact pHRI devices have been developed for use during walking [6]–[20]. However, these devices combine a unique hardware design with a specific type of controller, making it difficult to distinguish the contributions of the hardware vs the controller to effects on human gait. These devices also have performance limitations that make them ill-suited for testing how different types of controllers influence human behavior. Heavy weight [10], low speed [11], [12], and low bandwidth [10] may be unavoidable for mobile robots that must transport motors and power supplies.

Furthermore, existing devices have focused on improving how fast people walk [13]–[15] but not how they coordinate gait parameters such as step frequency and step length as they change speeds. Altering gait parameters in a targeted manner is an important function for robots designed to assist persons with physical disabilities or teach movement skills. During unaided human gait there is a constant relationship between step frequency and step length [16], [17], but altering this "walk ratio" is necessary for different contexts such as walking on stepping stones or avoiding obstacles. Step frequency and length relationships are also affected in a variety of motor pathologies, e.g. individuals with Parkinson's disease show difficulty modulating step length but not step frequency [18].

In prosthetics and exoskeleton pHRI research, laboratory testbeds or "emulators" have been highly effective for

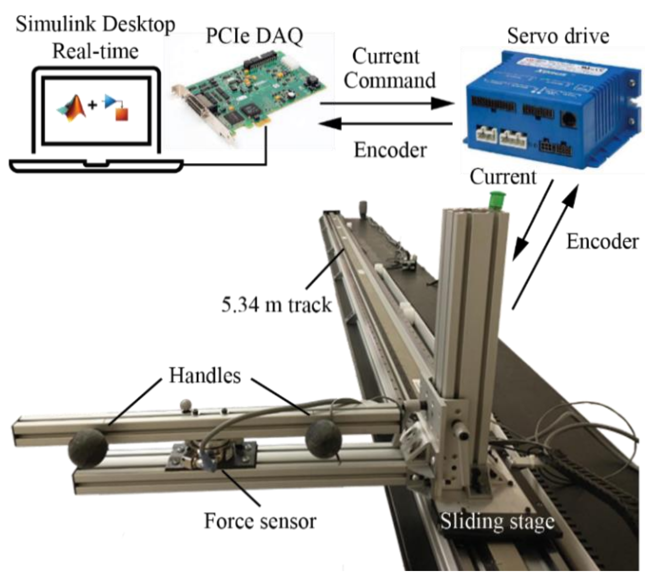

Fig. 1: Robotic emulator components and communication pathways

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quickly exploring a variety of device controllers and functionalities with fewer performance fidelity limitations compared to mobile, standalone devices [19]–[21]. Thus, our goal was to build a versatile high-fidelity emulator capable of testing a wide range of controllers that use hand interactions to alter human gait parameters, especially controllers inspired by human-human haptic communication.

Here we describe design and validation of the emulator, "Slidey," and demonstrate a potential application for altering human gait parameters. We demonstrate that Slidey has adequate performance to emulate a range of hand interactions during walking, and we present proof-of-concept that Slidey can decouple the coordination of the gait parameters step length and step frequency as gait speed increases in an unimpaired participant. We therefore show that Slidey has sufficient capabilities to be used as a robotic emulator to identify and test controllers that can be implemented in mobile robotic devices.

II. Device Design and Validation

A. Hardware design and specifications

Tto allow for overground walking across the range of possible human walking speeds while minimizing risk of injury to the human user, we chose a novel design that translates a sliding stage on a long, fixed track for our emulator (Fig. 1). The maximum translational displacement of >5 m allows most humans to walk several steps. As opposed to a mobile robot, a device that moves on a fixed track also consumes less of the device's power for self-locomotion and can achieve high speeds (Slidey can achieve a translational speed of 2.4 m/s) and high bandwidth control for emulating human physical interactions. The user interface is designed to be ergonomic and versatile, allowing adjustability for different modes of use and users with varying anthropometric measurements. The high-resolution (6.25 mN) force-torque sensor enables measurement and control of small forces relevant to haptic communication. In addition to the design of a small moving stage on a fixed track as opposed to a large mobile robot, other safety features are implemented via analog circuitry and digital controls.

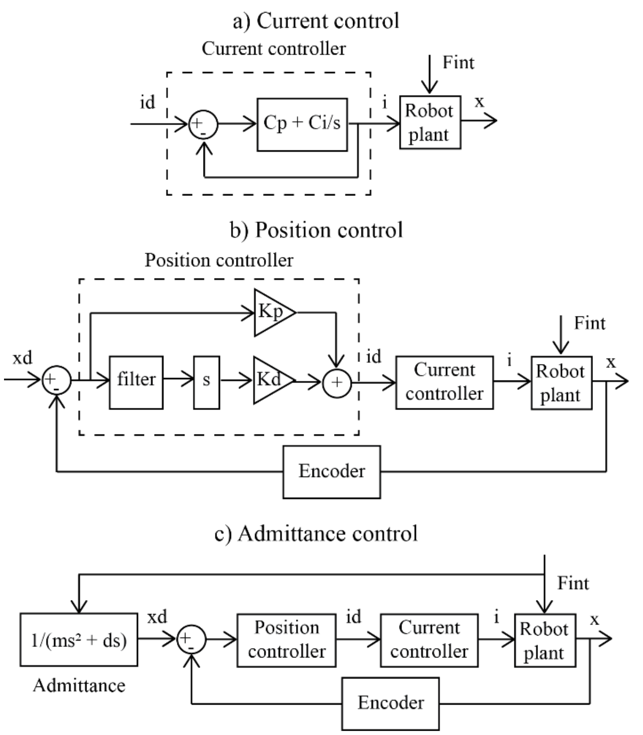

Fig. 2: Control diagrams for a) current control: *id* = desired current, *i* = actual current, *Cp* = proportional gain, *Ci* = integral gain, *Fint* = interaction force, *x* = actual position, b) position control: *xd* = desired position, *Kp* = proportional gain, *Kd* = derivative gain, and c) admittance control: *m* = virtual mass and *d* = virtual damping.

B. Control architecture and validation

A high-speed, high-precision, hierarchical control scheme enables versatile robot control (Fig. 2). For current control, Simulink Desktop Real-Time software (Mathworks, MA, USA) sends desired current commands to the feedback controller (Fig. 2a) running on the servo drive. Custom Simulink code was written to realize position (Fig. 2b) and admittance control (Fig. 2c).

The parameters for the current controller (Fig. 2a) on the servo drive were tuned using the auto-tuning function in CME2 software (Copley Controls, MA, USA) to "maximize smoothness" of operation. To characterize the frequency response of the current controller, we input sinusoids with amplitude of 2 Amps and frequencies logarithmically scaled between 1-1024 Hz. We calculated the -3dB bandwidth from the Bode plot to be between 512 and 1024 Hz (~651 Hz from linear interpolation).

Feedback gains for the closed-loop position controller (Fig. 2b) were manually tuned to result in smooth motion without high-frequency vibrations. As position commands from the high-level controller are converted into current commands in the low-level controller validated previously, we calculated the bandwidth of our system based on desired position inputs and actual position outputs. We input sinusoids with a velocity amplitude of 0.2 m/s and frequencies up to 20Hz and calculated the 3dB bandwidth to be 5.84 Hz. The system also does not have significant power in frequencies >10 Hz, which is important for avoiding high-frequency vibrations that can be sensed by human cutaneous mechanoreceptors.

We validated our admittance controller (Fig. 2c) by measuring actual and desired position while a person exerted sinusoidal forces on the handles of the device over a range of fixed frequencies during standing. While our device can render a wider range of admittances (virtual mass ≤ 10 kg, virtual damping ≤ 20 N/(m/s)), we chose admittance values of 5 kg and 2.5 N/(m/s) for our validation based on the human participant's preferred values. Our validation data showed a correlation of r = 0.997 between actual and desired position with a lag of 0.024s. Interaction forces remained within 30N, which is realistic for haptic communication.

III. Proof-of-concept Alteration of Spatiotemporal Gait Parameters Through Small Forces at the hand

We demonstrate that Slidey has sufficient performance to enable future studies to systematically alter the "walk ratio" between step frequency and step length. Specifically, we tested whether interactions at the hand could preferentially increase step frequency or step length as walking speed increases in a single participant.

A. *Experiment design and analysis*

We developed custom robot velocity profiles consisting of transient velocity pulses at varying frequencies (*fR*) superimposed on a constant velocity ramp of varying magnitude – which we termed "bias" (*b*) - implemented via position control (Fig. 3a). We hypothesized that *b* would affect average human walking speed (*v*) while *fR* would affect average human step frequency (*f*) (Fig. 3a-c). Given that average walking speed is the product of step frequency and step length (*L*), i.e. $v = f * L$, we varied *fR* and *b/fR* to target changes in human step frequency and step length, respectively. Because we wish to develop a robot that is intuitive to use, the participant was not given explicit instructions on how to walk with the robot other than to maintain a consistent arm/hand posture.

The main experiment had 3 conditions (Alter Gait Speed, Alter Step Frequency, and Alter Step Length), and each condition had 3 desired gait speeds (Below, Equal to, and Above the individual's preferred speed during walking without the robot). In the Alter Gait Speed condition, only velocity bias (without pulses) was changed to enforce gait speed changes. This control condition established the baseline ratio between step frequency and step length. The pulsed conditions aimed to alter either step frequency or step length with walking speed.

A young adult (age 27 years, height 1.85 m, weight 106 kg) without neurological or physical impairments was recruited from Emory University (IRB00082414) to participate in user testing. Retroreflective markers were attached to the participant's body according to the Lower Body Plug-in-Gait model with an additional marker at the left shoulder and recorded at 120 Hz with a 10-camera motion capture system (Vicon Nexus, Oxford, UK). Gait parameters of walking speed, step frequency, and step length were calculated from motion capture data of shoulder and heel markers (Fig. 3b, c).

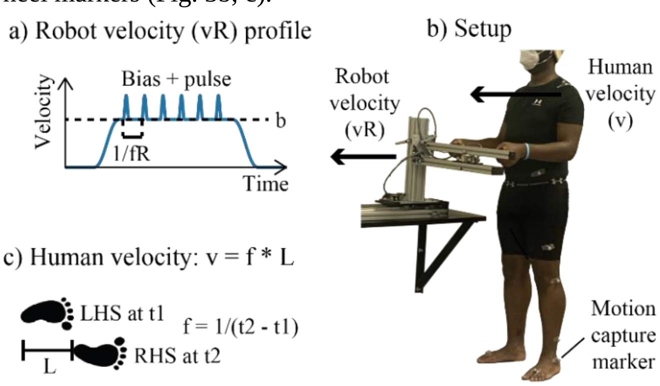

Fig. 3: Experiment design. a) Custom velocity profiles with velocity bias (*b*) and transient pulses at frequency (*fR)* were implemented in the robotic emulator to alter specific gait parameters. b) Participant kinematics were recorded via motion capture while they held the handle of the device and walked forwards. c) Human gait parameters of gait speed (*v*), step frequency (*f*), and step length (*L*) were calculated from motion capture data LHS = left heelstrike, RHS = right heelstrike, t1 and t2 = time of HS events.

B. *Results*

Kinematic results show that the pulsed robot velocity conditions resulted in intended changes in the ratio between step frequency and step length vs. the unpulsed control condition. Step frequency and step length increase at a fixed ratio as gait speed increases during the Alter Gait Speed control condition (blue data points and regression line in Fig. 4). Step frequency is preferentially altered with gait speed during the Alter Step Frequency condition (red in Fig. 4), as seen in the steeper regression line slope compared to the control condition. Step length is preferentially altered with gait speed during the Alter Step Length condition (yellow in Fig. 4), as seen in the shallower regression line slope compared to control. Due to the large variability in step frequency and length at slow gait speeds, we also performed regression without data from the Below level for each condition and found statistically significant differences in slopes between the Alter Step Length condition and the other two conditions (Fig. 4b).

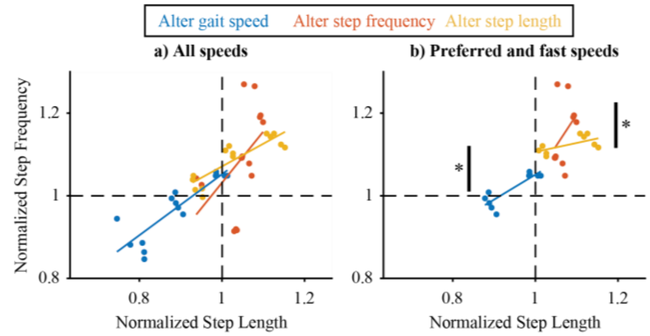

Fig 4: Changes in ratio between step frequency and step length in robot velocity pulse conditions. Color denotes gait parameter targeted. Dots denote individual trial data; lines denote linear regression to trial data. (*) indicates significantly different regression line slopes. Step frequency and step length are normalized to the participant's preferred values when walking without the robot. a) Regression including all levels of each condition. b) Regression excluding levels below preferred values results in significant differences in slopes.

IV. DISCUSSION

To our knowledge, this is the first pHRI robot capable of emulating a wide range of physical interactions at the hand during walking. The novel functionalities offered by Slidey can enable rapid testing and prototyping of device functionalities to guide the design of mobile robots for aiding gait. The versatile, high-fidelity emulator enables direct comparison of different controllers in one hardware platform and identification of the effects of these controllers on human gait. It can also be used to develop and test novel physical interaction controllers based on human-human haptic communication. Furthermore, our emulator establishes a tool for scientific studies investigating causal relationships between hand interactions and gait, enabling new principles of human-robot interactions to be determined.

As an example application, we show the feasibility of using the emulator not just to change how fast a person walks, but also how they coordinate stepping patterns. The effects were achieved without explicit instructions to the user, showing the potential for pHRI devices that require little to no user training. Such devices can assist persons with physical disabilities and teach movement skills to persons with or without disabilities in an intuitive manner.

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