

Improved Mobility with a Neutral, Motion-Amplifying Controller for an Experimental Exoskeleton

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ABSTRACT

The number of seniors is rising worldwide. Exoskeleton devices can help seniors regain their lost power, balance, and agility, thus improving their quality of life. Exoskeleton devices and control strategies assist human gait. A common strategy is to use oscillator-based controllers, which “lock in” with the gait and help the subject walk faster using a phase lead characteristic. Such strategies are limited to gait assist only and are less effective in more general movements. These controllers can be detrimental in critical cases such as when the leg needs to execute a fast reactive stepping to stop a fall. We present a control strategy for a hip exoskeleton, which assists human leg motion by providing motion amplification at the hip joint. The controller is “neutral” because it assists any leg motion, not only a gait, and can help avoid falls by assisting reactive stepping. Our control strategy modifies the joint dynamics of the coupled human-exoskeleton system such that the desired dynamic response is achieved while guaranteeing stability. We define assistance as reducing the impedance and increasing the admittance of the coupled system. The dynamic response of the leg is defined by the frequency response profile of the magnitude of integral admittance (torque-to-angle relationship) of the coupled human-exoskeleton system, and assistance occurs when this profile is higher than that of the unassisted leg for all frequencies of interest. Our controller produces hip joint motion amplification and results in larger and faster leg swing motions, and can help recover the seniors' power and agility.

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INTRODUCTION

World Health Organization (WHO) studies have estimated that between 2000 and 2050, the proportion of the world's population over 60 years will double from about 11% to 22% [1]. With aging, the human body tends to lose its power and agility and this drastically affects the range and quality of mobility that we otherwise take for granted. Exoskeleton devices can potentially help aging seniors regain their lost power and agility and make them more independent and self-reliant by helping them perform their activities of daily living (ADL).

Inherently correlated with the loss of power and agility, aging seniors also experience a general degradation of balance capability and an increased occurrence of fall. In the U.S. alone, an estimated 4.05 million seniors were treated in hospital emergency departments for fall-related fractures between 2001 and 2008 [2]. According to WHO's fact sheet on falls [3], adults older than 65 years (seniors) suffer the greatest number of fatal falls, and falls are the second leading cause of accidental or unintentional injury deaths worldwide. Assistive exoskeleton devices [4, 5] can help reinforce the balance capabilities of aging seniors, reduce their chance of fall and of catastrophic injuries, and thereby promote a lifestyle with safe mobility. Mobility is known to have a strong positive effect not only on the physiological processes such as respiratory and circulatory systems, but also on the psychological state and morale of the person.

A number of exoskeleton devices and control strategies have been developed that aim at assisting human mobility. A common strategy is to use controllers that are based on oscillators [6, 7] such as van der Pol [8] or Duffing [9] or perhaps employ central pattern generator (CPG) [10]. Such controllers lock in with the gait cycle and through phase lead creates the effect of forward push to the joint motion. However, such strategies are limited to assisting cyclic motions and are mainly applicable to gait assist. For general movements and activities that involve frequent variations including start/stop and direction change, these controllers are less effective. In fact, these controllers can be detrimental in critical cases such as when the leg needs to execute fast reactive stepping in order to stop a potential fall.

It has been conjectured that the ideal joint level behavior of an assistive exoskeleton should be that of a pure torque source. In other words, the physical and dynamics footprint of the exoskeleton on the subject should be as small as possible, and should be manifested only through the assistive torque. This translates to the fact that the device, ideally, should be able to perfectly compensate for its own dynamics. Additionally, the exoskeleton should *never* oppose the human. This means that the exoskeleton's torque profile should be in harmony with the motion intent of the person. The other desirable exoskeleton properties are that its controller should be highly responsive (high bandwidth) and stable, and the device should be minimally invasive.

with sensing and actuation. Finally, and quite importantly, the exoskeleton should not exhibit unrelated detrimental effects e.g., a gait assist exoskeleton should not negatively affect balance capability.

We propose that exoskeletons that are meant for a general range of activities must additionally possess the property of *neutrality*. A neutral exoskeleton is one that can assist the human joint at a fundamental “joint motion” level and is not partial to a specific motion pattern or a specific activity. Implied in this description is the fact that the exoskeleton controller does not control any “higher level” description of the motion undertaken by the human. Consequently, it simply assists the motion initiated by the human and does not modify the motion with any higher purpose. The philosophy behind this controller is that the human possesses the knowledge of the best limb movement that is required in any given situation, even though they may not always have the physical ability to execute it promptly or fully. The intended effect is that the control law executed by the coupled human-exoskeleton system is unchanged from what the human itself wanted to execute, only that the exoskeleton makes available additional joint torque.

In this paper, we present a novel control strategy for the Honda Stride Management Assist (SMA) exoskeleton device [11]. The SMA device is a 2-DOF exoskeleton device meant for assisting the hip joints as shown in Figure 1. Our control approach, called the *Integral Admittance Shaping*, assists the human by virtually modifying the human leg dynamics such that its effective impedance is reduced and effective admittance is increased. This provides motion amplification (equivalently, torque reduction) to the hip joint. The controller is neutral in the sense described above. In addition to assisting in walking, this controller is equally suited for helping humans in more general ADL activities. Particularly beneficial is its potential role in fall avoidance by facilitating a faster and longer step in reactive situations.



Figure 1. Honda Stride Management Assist (SMA) device.

In the present implementation of integral admittance shaping, the exoskeleton exhibits active impedance at its interaction point with the human body (the location of fastening straps just above the knee joint). In simplest terms, active impedance can be thought of as the generalized version of a negative mass, though the effects of a

negative spring and negative damper are also present in the impedance. A negative mass is an active element and the control system displaying an active property is unstable. Our controller achieves active impedance through the *positive* feedback of position, velocity and acceleration. Consequently, this controller is unstable in isolation. One may legitimately ask the wisdom behind deliberately creating an unstable exoskeleton controller. The response to this concern lies in the concept of coupled stability.

The human body, by virtue of its inherent visco-elastic properties, is capable of stabilizing interacting unstable systems through contact. We have experienced this when, for example, by simply touching a vibrating machine component, we can render it stable. While our isolated exoskeleton, displaying active impedance, is unstable, the coupled human-exoskeleton system can still be stable. In this work, we show how active exoskeleton controllers can be designed while still guaranteeing coupled stability.

While the coupled human-exoskeleton system must satisfy the coupled stability condition, we take into account an additional level of system interaction, in which the coupled human-exoskeleton system interacts with a third entity, such as the ground. If the coupled human-exoskeleton system possesses the property of passivity [12], it remains stable while interacting with other passive systems. Noting that the ground and other typical environments are passive, we require that our integral admittance shaping controller guarantees both coupled stability and passivity.

In this paper, the controller is implemented as an optimization algorithm that determines the effective moment of inertia, joint damping coefficient and joint stiffness coefficient for a desired assisted human limb dynamics. We experimentally demonstrate that our controller produces hip joint motion amplification and results in larger and faster leg swing motions on humans. Thus, our controller has the potential to recover the lost power and agility of the lower limbs to aging seniors.

EQUATIONS OF MOTION OF A COUPLED HUMAN-EXOSKELETON SYSTEM

In this work, we use 1-DOF linear models for the leg and the exoskeleton. The 1-DOF leg model is an approximation of the extended leg with locked-knee swinging about the hip joint. This model captures the dynamics of the swinging phase of the gait cycle. The linear leg model is defined by its moment of inertia I_h , damping coefficient b_h and stiffness coefficient k_h , while the corresponding parameters $\{I_e, b_e, k_e\}$ are used to define the exoskeleton model as shown in Figure 2. The coupling between the leg and the exoskeleton is not rigid by virtue of the muscles, tissues, and structural and joint compliance of the exoskeleton. To model this, we use a linear spring-damper with damping coefficient b_c and stiffness coefficient k_c as shown in Figure 2.

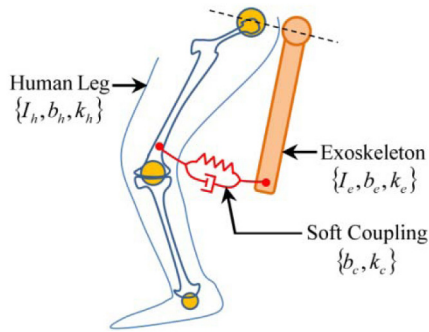


Figure 2. Coupled human-exoskeleton system.

The linear equations of motion of the coupled human-exoskeleton system are given by

$$I_h \ddot{\theta}_h(t) + b_h \dot{\theta}_h(t) + k_h \theta_h(t) = \tau_h(t) - \tau_c(t) \quad (1)$$

$$I_e \ddot{\theta}_e(t) + b_e \dot{\theta}_e(t) + k_e \theta_e(t) = \tau_e(t) + \tau_c(t) \quad (2)$$

$$b_c(\dot{\theta}_h(t) - \dot{\theta}_e(t)) + k_c(\theta_h(t) - \theta_e(t)) = \tau_c(t) \quad (3)$$

Here, τ_h and τ_e are the hip joint torques of the human and exoskeleton respectively, and θ_h and θ_e are the human and exoskeleton hip joint angles respectively. The coupling torque at the hip joint corresponding to the interaction between the human leg and the exoskeleton is denoted by τ_c .

The impedance [13] $Z_h(s)$ and admittance [13] $Y_h(s)$ transfer functions of an isolated human leg are given by

$$Z_h(s) = \frac{I_h s^2 + b_h s + k_h}{s}, \quad (4)$$

$$Y_h(s) = \frac{s}{I_h s^2 + b_h s + k_h}. \quad (5)$$

In this work, we use the integral of the admittance, called *integral admittance*, to characterize the joint dynamics. The integral admittance transfer function $X_h(s)$ is given by

$$X_h(s) = \frac{1}{I_h s^2 + b_h s + k_h}. \quad (6)$$

The admittance transfer function $Y_e(s)$ of the isolated exoskeleton and the impedance transfer function $Z_e(s)$ of the isolated coupling element are given by

$$Y_e(s) = \frac{s}{I_e s^2 + b_e s + k_e} \quad (7)$$

$$Z_c(s) = \frac{b_c s + k_c}{s} \quad (8)$$

Using (5), (7), (8), the equations of motion in (1), (2), (3) with an exoskeleton control transfer function $U_e(s)$ can be represented as a block diagram shown in Figure 3(a).

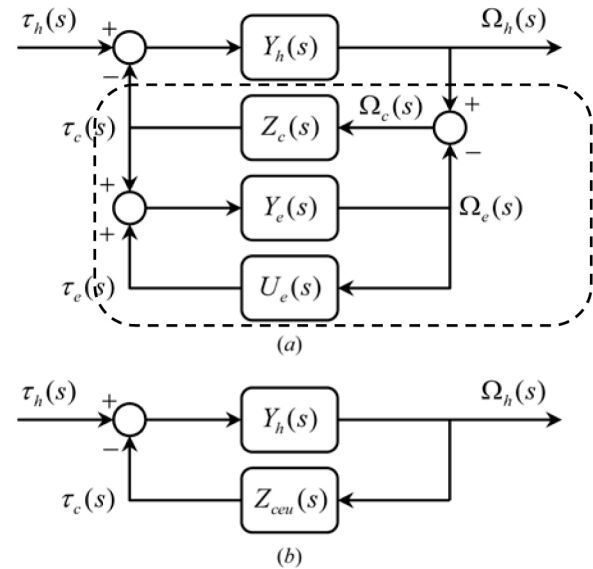


Figure 3. Block diagram of the closed-loop coupled human-exoskeleton system.

The outlined region in Figure 3(a) can be reduced to a single transfer function $Z_{ceu}(s)$ given by

$$Z_{ceu}(s) = \frac{Z_c(s)}{1 + Z_c(s) Y_{eu}(s)} \quad (9)$$

as shown in Figure 3(b). The transfer function $Y_{eu}(s)$ in (9) is given by

$$Y_{eu}(s) = \frac{Y_e(s)}{1 - Y_e(s) U_e(s)}. \quad (10)$$

The impedance transfer function $Y_{heu}(s)$ of the closed-loop system in Figure 3(b) is given by

$$Y_{heu}(s) = \frac{Y_h(s)}{1 + Y_h(s) Z_{ceu}(s)}, \quad (11)$$

and its integral admittance transfer function $X_{heu}(s)$ is given by

$$X_{heu}(s) = \frac{X_h(s)}{1 + Y_h(s) Z_{ceu}(s)} \quad (12)$$