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Taking both sides: seeking symbiosis between intelligent prostheses and human motor control during locomotion

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Abstract
Robotic lower limb prostheses aim to replicate the power-generating capability of biological joints during locomotion to empower individuals with lower limb loss. However, recent clinical trials have not demonstrated clear advantages of these devices over traditional passive devices. We believe this is partly because the current designs of robotic prothesis controllers and clinical methods for fitting and training individuals to use them do not ensure good coordination between the prosthesis and user. Accordingly, we advocate for new holistic approaches in which human motor control and intelligent prosthesis control function as one system (defined as human–prosthesis symbiosis). We hope engineers and clinicians will work closely to achieve this symbiosis, thereby improving the functionality and acceptance of robotic prostheses and users' quality of life.

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Introduction

New technologies for robotic lower limb prostheses are becoming more accessible to individuals with lower limb loss (LLL) [1,2]. These prostheses can mimic the torque-generating capabilities of biological joints to empower those with LLL; yet, even during the most common locomotor task — walking — these advanced prostheses fail to show clear advantages over energetically passive devices for the users [3–7]. For example, it is well known that an appropriate level of ankle push-off power is responsible for energetically efficient walking in humans [8]. For individuals with transtibial LLL wearing passive ankle–foot prostheses, the metabolic cost of transport is considerably high. Theoretically, powered prosthetic ankles can restore the push-off function of the missing ankle and therefore improve the user's energetics and preferred speed during walking. In reality, this benefit has not been consistently shown [5–7,9].

What causes this discrepancy? One plausible explanation is poor human–prosthesis coordination [6]. Human locomotion is a complex, dynamic process that involves the coordination of many joints controlled by one unified controller (the human nervous system). In addition, innate musculoskeletal structures, such as bi-articular muscles, contribute to the coordination of adjacent joints. When individuals with LLL wear a robotic prosthesis (i.e. a human–prosthesis system), the innate mechanism for between-joint coordination is altered, leading to two different controllers: (1) the human nervous system, which operates the intact joints and body segments, and (2) the computerized controller of the robotic prosthetic joints. The restoration of normal gait requires good coordination between these two controllers to merge the mechanics of the biological and prosthetic joints. Unfortunately, with current prosthesis designs and clinical methods, these controllers are largely disconnected functionally. On the one hand, computerized controllers in robotic prostheses do not consider factors such as motor impairment or compensatory motor strategies used by users, and they are not designed to optimize the overall gait performance of human–prosthesis systems. On the other hand, individuals with LLL do not always adapt or learn to use the active power provided by the prosthesis effectively or efficiently.

Hence, to maximize the walking function of individuals who wear advanced robotic lower limb prostheses, we believe the prosthesis controller and the user's motor control system must demonstrate good coordination and coadaptation to function seamlessly as one entity (defined as human–prosthesis symbiosis here). Although human–robot interaction or collaboration has been studied extensively [10,11], the symbiotic relationship between robotic prosthesis legs and their users has not, partly because robotic prosthetic legs have only become available within the last 10 years. Hence, in this article, we reviewed the results and limitations of recent research on the structures of robotic prosthesis controllers, approaches to optimizing the performance of these controllers, and user behaviors when interacting with these controllers during walking; we then proposed the concept of human–prosthesis symbiosis be considered in engineering, biomechanical, and clinical approaches to improve mobility and quality of life among individuals with LLL. Although most of the relevant research that has been conducted has included only individuals with unilateral LLL due to difficulty obtaining sufficient sample sizes, we believe the same symbiosis concept can be applied to those with bilateral LLL, as well as other individuals with neurological deficits (via exoskeletons).

Intelligent prosthesis control and its effects on the human–prosthesis system

Prosthesis control to enable walking

Most of the existing control methods for robotic lower-limb prostheses aim to enable people with LLL to walk with "normative" prosthesis ankle/knee kinematics or kinetics [12–15], which are defined for specific gait phases based on the biomechanics of individuals without LLL. Therefore, the controller must monitor each gait phase. Typically, discrete gait phases (e.g. the double/single stance and swing phases), often used in the field of biomechanics, are defined and estimated via onboard sensors [12,13,16]. This type of controller is called a finite-state machine. The concept of virtual constraints has recently been used to characterize the continuous coordination of kinematics among lower-limb joints within a gait cycle in persons without LLL [14,15]. By monitoring the residual thigh motion (approximate hip angle) in people with transfemoral LLL, for example, the controller can continuously adjust the prosthetic knee and ankle angles during walking based on predefined joint coordination constraints. These controllers directly coordinate with the action of the user's residual limb and yields better adaptability to varied walking speeds and inclination angles than do discrete finite-state machines. They even enable users to walk backwards and kick their leg.

One major challenge is how to predefine the prosthesis control parameters based on the gait biomechanics of persons without LLL. Individuals with LLL demonstrate very different gait patterns from each other and from those without LLL, partly due to weakness in the intact joints [17], decreased proprioception [18], poor socket fit [19], etc. Since it is difficult to directly model these factors in prosthesis control, the control parameters need to be modified for individual users, even when the goal is to merely reproduce "normative" joint kinematics or kinetics to enable walking [1–5,13]. In clinics, the parameters are tuned manually and heuristically by prosthetists when each individual walks with a robotic prosthesis. Recently, our research group developed new machine learning approaches, such as an expert system [20] and model-free reinforcement learning (RL)-based optimal adaptive control [21–23], to reduce this burden on prosthetists. RL-based methods are especially powerful because they are based on well-known theories in adaptive optimal control and can develop prosthesis tuning policies through trial-and-error learning in real time while the user walks with the prosthesis. RL is model-free because it does not require an explicit mathematical model to describe the human motor deficits and human–prosthesis system or prior tuning knowledge from prosthetists. RL has excellent scalability and can tune high-dimensional control spaces. More importantly, RL results in a tuning policy that can adaptively adjust prosthesis control parameters across different timeframes and walking environments (e.g. ramp ascent) [23].

Prosthesis control to optimize walking function

Now that many control methods can enable walking, researchers and engineers are currently focused on modifying the prosthesis control parameters to improve users' gait performance (indicated by gait symmetry [21], balance [24], and energetic expenditure [25]) and perceived preference [25] during walking. These factors are important for improving the walking function of individuals with LLL, that is, their capability to walk at normal speeds with improved endurance, walk with appropriate loading patterns to prevent the development of secondary health issues, and walk safely and confidently in real-world environments.

Unfortunately, robotic prosthesis controllers have not been optimized to maximize users' gait performance or preferences yet. One critical knowledge gap is whether — and if yes, how — robotic prosthesis or exoskeleton controllers influence the user's gait performance, preferences, and even tissue health [26]. Without such knowledge, the use of gait performance measures as prosthesis control optimization goal(s) can be challenging. Only a few related studies have been conducted [24,25,27–30]. One research group developed a novel ankle prosthesis emulator that can precisely simulate various prosthesis joint mechanics with a powerful off-board motor [31]. This emulator enabled the systematic study of the influence of a control parameter (such as push-off work [24,25] or timing [27]) on gait performance measures, including the metabolic cost, balance, preference, and perceived balance of prosthesis users. Our group examined the influence of 12 impedance control parameters of a robotic prosthesis knee during an entire stride on gait temporal and spatial symmetry [28]. Among these studies, only two were conducted in individuals with LLL, with small sample sizes [25,28]. In general, the results of these studies showed that the effects of prosthesis control vary largely across individuals with LLL. Prosthesis control cannot directly explain the changes in gait performance measures; near-normal gait performance cannot be completely achieved by adjusting the prosthesis control alone because gait performance also depends on the movement of the user, with large interindividual variability.

To optimize robotic prosthesis controllers to maximize users' walking function, many technical challenges must be solved. This requires the prosthesis controller to (1) treat the human and robotic prosthesis as one entity, which is difficult to model; (2) monitor the human—prosthesis system state (e.g. gait performance measures) beyond the gait phases and residual limb motion only; and (3) adapt to the physical conditions of individual users (e.g. height, weight, hip strength), which also vary within users over time. One idea is to develop a personalized musculoskeletal model and use computer simulations to optimize the wearable robot control parameters [32]. Another novel and promising solution is to optimize the wearable device control heretically with human-in-the-loop based on (1) search-based methods [33—36] or (2) model-free, reinforcement learning-based optimal adaptive control [21,22]. With this method, the responses of the human—robot system (e.g. the gait performance measures) to control settings can be directly assessed during walking. The search-based optimization methods iteratively search for an extremum on the system response surface to determine the optimal control parameters, while RL-based optimal adaptive controllers learn and approximate robot control policies by determining minimized/maximized cumulative costs/rewards, which can directly reflect gait measurements. Search-based optimization has been successfully applied to robotic exoskeletons to minimize the metabolic cost of transport; however, it has been only successfully demonstrated in able-bodied, healthy individuals [34,35], not in people who have motor deficits. RL-based optimal adaptive control has been used to personalize robotic prosthesis/exoskeleton control; however, the optimization goal is mainly to produce desired device joint kinematics [21,37,38] rather than desired walking function parameters in human users. Given the novelty and promising yet preliminary results, we believe more research and development on such human-in-the-loop methods are needed to make them clinically viable for robotic prosthesis personalization and intrauser adaptation and maximize walking function in individuals with LLL.

Influence of human control and adaptation on the human–prosthesis system

There is increasing evidence that individuals' motor control significantly influences the function of robotic prostheses during gait. When tuning a robotic knee controller to achieve desired knee kinematics (in terms of both magnitude and timing), we found that the prosthesis controller cannot precisely regulate the timing of the knee profile due to the significant influence of human actions on gait event timing [21]. We also found that users do not always make effective use of the active torque provided by the robotic prostheses [6]. We observed that when walking with a manually tuned ankle—foot prosthesis, some people did not move their residual shank and amputated limb to the appropriate position when the active propulsive torque was provided, thereby directing the prosthesis-side limb more vertically (upward) rather than anteriorly (forward) [6]. Such human motor behaviors reduce the efficiency of energy transfer from the robotic prosthesis in walking, even at the local joint level. Interestingly, a very similar phenomenon has been also observed with wearable ankle exoskeletons [39].

These results underscore the importance of training users to adjust their motor patterns and effectively use the power provided by wearable robots for improved locomotion. Human movement control is even more critical when the goal is to improve gait performance. Many engineers have focused on optimizing the prosthesis control side. However, the prosthesis is only a subsystem and affects gait performance to a limited extent at the system level; the behaviors of the user, the other subsystem, influence and even dominate some gait performance measures. Nevertheless, little attention has been paid to optimize gait biomechanics when people walk with robotic prostheses. For example, when a powered prosthesis is fit in clinics, individuals with LLL practice walking on different terrains while a prosthetist manually tunes the prosthesis control parameters. It takes only a couple of hours, and this process is insufficient to guarantee human—prosthesis symbiosis regarding gait performance [6]. In research settings, users are given time (ranging from 20 min to three weeks) to practice walking with a new device in a laboratory or at home. However, there are currently no standards for how to properly instruct them to use the new device or determine when acclimation is complete [40]. The assumption that users can automatically adapt to and coordinate with robotic prostheses by only practicing walking (without instructions) may be questionable. This is because the abnormal gait patterns of individuals with LLL may be partly derived from a lack of knowledge on how robotic prostheses function and the transfer of a maladaptive motor pattern that they learned when using their passive devices [41]. Instead, device-specific training is necessary for users to learn the appropriate gait patterns to best use the power produced by modern prostheses and achieve optimal gait performance.

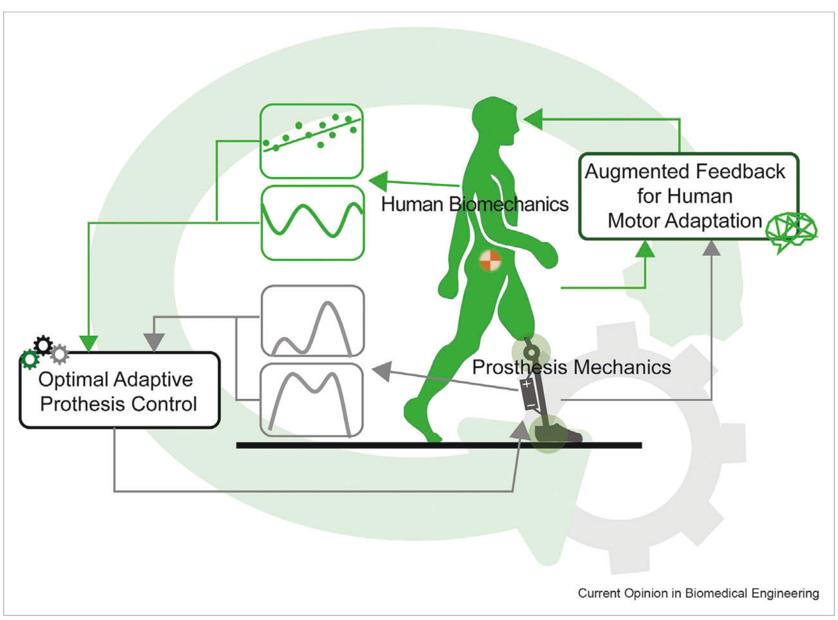
There are several engineering methods that can be used to facilitate training and movement learning to help people with LLL coordinate with the action of robotic prostheses. One approach is to use augmented biofeedback [17,41–43] to cue the user to make certain modifications (e.g. residual limb position, gait timing, loading) based on the action of prosthesis to achieve human–prosthesis coordination. This type of training can be even carried out in the real world due to recent advancements in wearable sensors and augmented reality [44]. In addition, providing feedback of the prosthesis' action (proprioception) via surgical techniques and neural interfaces [18] or haptic devices [45] may enhance the user's awareness of the machine's states and lead to coordinated body movements.

Future directions for human–prosthesis symbiosis

In our opinion, to maximize the benefits of modern robotic prostheses for individuals with LLL, it is necessary for both the user and robotic controller to function together (Figure 1). For prosthesis intelligent control, the controllers need to adapt to individual user impairments and motor behaviors, sense the overall system states, and optimize human–prosthesis gait performance measures. For human movement control, it is essential to communicate the prosthesis system states to the user and for him or her to learn to move appropriately to maximize the energy transferred from the robotic device. This requires (1) research and innovations on the optimal adaptive control of robotic prostheses and user training strategies for effective coordination with robotic devices and (2) collaborations among researchers in biomedical engineering, biomechanics, and rehabilitation clinics so that the behaviors of both systems are appropriately considered.

One challenge in implementing this concept is identifying a paradigm that can promote human–prosthesis coadaptation. Specifically, should the intelligent machine and human motor control systems adapt concurrently or alternately? We must first understand the learning rates of and interactions between the two systems. Another challenge is determining which common objective(s) for human–prosthesis systems yield the highest level of symbiosis. Many challenges in formulating and resolving this multiobjective optimization problem for human–prosthesis systems remain. Furthermore, merging human motor control with computerized prosthesis control, as discussed in this article, is one way to enable symbiosis; however, it cannot fully address situations in which immediate adaptation is required, such as obstacle avoidance [46], and tasks that are not preprogrammable, such as playing tennis. For these situations, the users should dominate the prosthesis operations. This requires direct efferent neural control of the robotic prosthesis joint [18,47,48], which is a future research direction related to human–prosthesis symbiosis. Finally, our proposed framework can be extended to other assistive devices including exoskeletons for people with neuromotor deficits. These topics related to physical human–robot interactions

Figure 1



Human–prosthesis symbiosis requires seamless coordination and coadaptation between prosthesis control and human mov gait control.

should be explored in parallel to achieve human–robot symbiosis for everyone who may benefit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Although the powered ankle prosthesis that is commercially available was designed to provide positive mechanical work around the ankle joint during walking, the amount of net ankle work varied across people with LLL. Less ankle work was coupled with an earlier push-off timing and a more vertical residual shank, indicating suboptimal human-prosthesis coordination.

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