Proceedings of IMECE2005
2005 ASME International Mechanical Engineering Congress and Exposition
November 5-11, 2005, Orlando, Florida USA

IMECE2005-80109

HYBRID CONTROL OF THE BERKELEY LOWER EXTREMITY EXOSKELETON (BLEEX)

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ABSTRACT

The first functional load-carrying and energetically autonomous exoskeleton was demonstrated at U.C. Berkeley, walking at the average speed of 0.9 m/s (2 mph) while carrying a 34 kg (75 lb) payload. The original BLEEX sensitivity amplification controller, based on positive feedback, was designed to increase the closed loop system sensitivity to its wearer's forces and torques without any direct measurement from the wearer. The controller was successful at allowing natural and unobstructed load support for the pilot. This article presents an improved control scheme we call "mixed" control that adds robustness to changing BLEEX backpack payload. The walking gait cycle is divided into stance control and swing control phases. Position control is used for the BLEEX stance leg (including torso and backpack) and the sensitivity amplification controller is used for the swing leg. The controller is also designed to smoothly transitions between these two schemes as the pilot walks. With mixed control, the controller does not require a good model of the BLEEX torso and payload, which is difficult to obtain and subject to change as payload is added and removed. As a tradeoff, the position control used in this method requires the human to wear seven inclinometers to measure human limb and torso angles. These additional sensors require careful design to securely fasten them to the human and increase the time to don (and doff) BLEEX.

KEYWORDS

BLEEX, exoskeleton, human-machine, wearable robotics, control, load support, sensitivity amplification.

INTRODUCTION

BLEEX was first unveiled in 2004, at U.C. Berkeley's Human Engineering and Robotics Laboratory (Fig. 1). The primary objective of this project is to develop fundamental technologies that augment human strength and endurance during locomotion. The first field-operational lower extremity exoskeleton (commonly referred to as BLEEX) is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of heavy loads can be mounted. This system provides its pilot (i.e. the wearer) with the ability to carry significant loads on his/her back with minimal effort over any type of terrain. BLEEX allows the pilot to comfortably squat, bend, swing from side to side, twist, and walk on ascending and descending slopes, while also offering the ability to step over and under obstructions while carrying equipment and supplies. The overall concept of this lower extremity exoskeleton is that the human provides an intelligent control system for the exoskeleton while the exoskeleton actuators provide most of the strength necessary for walking [1,2].

Fig. 1: Berkeley Lower Extremity Exoskeleton (BLEEX) and pilot.

BLEEX has numerous potential applications; it can provide soldiers, disaster relief workers, wildfire fighters, and other emergency personnel the ability to carry heavy loads such as food, rescue equipment, first-aid supplies, communications gear, and weaponry, without the strain typically associated with demanding labor.

The control algorithm was designed to increase the closed loop system sensitivity to its wearer's forces and torques without any measurement from the wearer. As an alternative, this article presents the mixed control scheme. Position control is used for the stance leg (including torso) and a sensitivity amplification controller is used for the swing leg.

Much of exoskeleton control theory was derived from early work in haptic interfaces and human machine interaction [3-10]. Many control approaches have been used for different exoskeletons, such as zero-moment point control, myoelectric sensing, and force control [1,11-13]. Among them, master-slave control is the one most closely related to our mixed control method. Master-slave control has traditionally been used in tele-robotics systems where the objective is to mimic the movements of a human operator. Master-slave control was implemented on an exoskeleton in the late 1960's by General Electric. Their research team created a 30 DOF full-body exoskeleton called Hardiman [14]. The Hardiman employed two overlapped structures: a load bearing outer exoskeleton and a lightweight sensing inner exoskeleton attached to the human. The inner exoskeleton works like a sensor suit and it measures the human position. The position feedback controller uses this data to cause the load bearing outer exoskeleton to track the human position. Unsupported walking was never achieved using this control scheme due to limitations in the control performance and safety of the overall system. Unfortunately, there are few documents from the Hardiman project publicly available. The Hardiman method attempted to match the machine joint angles one-to-one with the corresponding human joint angles, which required that exoskeleton link lengths match human link lengths and required that the human be able to move with respect to the load bearing exoskeleton. Ultimately, the bulky design and complex interface of the outer exoskeleton meant that these requirements could not be realized simultaneously.

MECHANICAL DESCRIPTION

BLEEX, as shown in Fig. 1, is a system with 14 degrees of freedom. Each BLEEX leg has three degrees of freedom at the hip, one degree of freedom at the knee, and three degrees of freedom at the ankle. Both the flexion-extension and abduction-adduction degrees of freedom at the hip are actuated. The knee has one flexion-extension degree of freedom that is actuated. The ankle plantar-dorsi flexion (in the sagittal plane) is also actuated. The other three degrees of freedom (i.e., rotation and abduction-adduction at the ankle and rotation at the hip) are equipped with passive impedances using steel springs and elastomers. In summary, each BLEEX leg has four powered degrees of freedom: hip joint, knee joint and ankle joint in the sagittal plane and a hip abduction-adduction joint. In the mixed control experiment, only the sagittal plane is considered and hip abduction-adduction joints are not powered.

The pilot and BLEEX have mechanical connections at the torso and the feet; everywhere else the pilot and BLEEX have compliant or periodic contact. The connection at the torso is made using a custom vest. One of the essential objectives in the design of these custom vests was to allow the distribution of the forces between BLEEX and the pilot, thereby preventing abrasion. The vest is made of several hard surfaces that are compliantly connected to each other using thick fabric. The adjustment mechanisms in the vest allow for a snug fit to the pilot. The vest includes rigid plates (with hole patterns) on the back for connection to the BLEEX torso [15].

MIXED CONTROL OF BLEEX

Looking at the entire walking gait cycle, the swing leg undergoes large motions but it is only supporting its own weight—it needs relatively small torques and high bandwidth. The stance leg goes through a small motion but supports the entire torso and payload—it needs large torques and relatively low bandwidth. Based on these observations, mixed control is put forward. For a single leg, the walking gait cycle is divided into a load support stance phase and an unloaded swing phase. With mixed control, position control is applied to the leg when it is in the stance phase and a positive feedback based sensitivity amplification controller is applied to the swing leg. At any instant, for any powered joint, only one control method is determining the control signal.

For the stance leg (i.e. the leg that is on ground), position control is used to servo BLEEX joint angles to track the human's joint angles. Since the BLEEX torso weight is carried by the stance leg, there is no need to know the mass and center of gravity (CG) properties of the torso. For the swing leg, a positive feedback sensitivity amplification controller, identical to the one presented in [1], is used. Provided the controller has a precise dynamic model of the BLEEX structure, this controller allows BLEEX to track rapid human limb motions without impeding the human. Thus, robust stability (position controlled stance leg) and a high sensitivity to the human forces and torques (sensitivity amplification controlled swing leg) can be maintained simultaneously.

Swing phase: sensitivity amplification

The sensitivity amplification controller presented in [1] needs no direct measurements from the pilot or the human-machine interface (e.g. no force sensors between the two). Instead, the controller estimates, based on measurements (accelerometers and encoders) from the exoskeleton only, how to move so that the pilot feels very little force. This has been shown to be an effective method of generating locomotion when the contact location between the pilot and the exoskeleton is unknown and unpredictable (i.e. the exoskeleton and the pilot are in contact in variety of places). The basic principle for the control of BLEEX requires a high level of sensitivity in response to the forces and torques imposed by the pilot.

The control of the exoskeleton is motivated below by considering a planar 1 DOF exoskeleton system—a human leg attached or interacting with a 1 DOF exoskeleton leg in a swing configuration (no interaction with the ground). For simplicity, the exoskeleton leg is considered to be a rigid link pivoting about a revolute joint and powered by a single actuator.

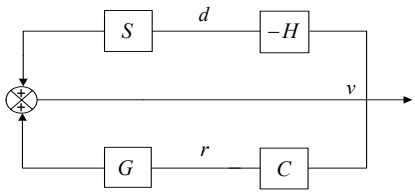

Fig. 3: This block diagram shows how the exoskeleton moves. The upper feedback loop shows how the human moves the exoskeleton through applied forces. The lower feedback loop shows how the controller drives the exoskeleton independent of the human feedback loop.

Fig. 3 shows the control block diagram, where G represents the transfer function from the actuator input, r, to the exoskeleton angular velocity, v (actuator dynamics are included in G). In the case where multiple actuators produce controlled torques on the system, r is the vector of torques imposed on the exoskeleton by the actuators. The sensitivity transfer function, S, represents how the equivalent human torque affects the exoskeleton angular velocity. S maps the equivalent pilot torque, d, onto the exoskeleton velocity, v. The pilot force on the exoskeleton, d, is a function of both the pilot dynamics, H, and the kinematics of the pilot limb (e.g., velocity, position, or a combination thereof). In general, H is determined primarily by the physical properties of the human dynamics. Here we assume H is a nonlinear operator representing the pilot impedance as a function of the pilot kinematics as shown in (1). Many other more detailed models of H also exist [16,17], but are not necessary for this discussion.

$$d = -H(v) \tag{1}$$

Positive feedback control is used such that our goal of sensitivity amplification is achieved:

$$|S_{NEW}| > |S| \qquad \forall \omega \in (0, \omega_0) \tag{2}$$

or alternatively $|1 + GC| < 1 \qquad \forall \omega \in (0, \omega_O)$ (3)

where ω_O is the exoskeleton maneuvering bandwidth and S_{NEW} is the closed-loop sensitivity transfer function from human torque, *d*, at the input to the exoskeleton motion, *v*, at the output as shown in (4)

$$S_{NEW} = \frac{v}{d} = \frac{S}{1 - GC} \tag{4}$$

Exoskeleton control requires a totally opposite goal from classical and modern control theory: *maximize the sensitivity of the closed loop system to forces and torques*. In classical servo problems, negative feedback loops with large gains result in small sensitivity within a bandwidth, which means that they reject forces and torques (usually called disturbances). However, our design goal states that the exoskeleton controller needs a large sensitivity to forces and torques.

To achieve a large sensitivity function, we use the inverse of the exoskeleton dynamics as a positive feedback controller so that the loop gain for the exoskeleton approaches unity (slightly less than 1). In general, the use of positive feedback with a controller is chosen as:

$$C = \left(1 - \alpha^{-1}\right) G^{-1} \tag{5}$$

where α is the amplification number greater than unity.

If $\alpha = 10$, then $C = 0.9G^{-1}$, and the new sensitivity transfer function is $S_{NEW} = 10S$ (ten times the force amplification). Equation (5) simply states that a positive feedback controller needs to be chosen as the inverse dynamics of the system dynamics scaled down by $(1 - \alpha^{-1})$. Note that (5) prescribes the controller in the absence of unmodeled high-frequency exoskeleton dynamics. In practice, C also includes a unity gain low pass filter to attenuate the unmodeled high-frequency exoskeleton dynamics that may not be captured in the model, G^{-1}.

The above simple solution comes with an expensive price: robustness to parameter variations. In order to get the above method working, one needs to know the dynamics of the system well. When this method is used for all phases of the walking gait cycle, the machine CG, and mass must be known very well. Obtaining a good model of each BLEEX link is not hard since, as the designer, we can control their dimension and construction. However, obtaining a good model of torso is nontrivial because the torso includes a variable payload. In addition, this method is computationally very expensive. In the single stance phase, the controller must calculate the full inverse dynamics of a 7 DOF serial chain of links every time through the control loop. Even on a fast modern microprocessor, this can consume the bulk of the 500us computation window corresponding to our 2Khz control update rate. As will be shown later, the mixed method allows us to circumvent much of this computation [18].

Implementation of the Sensitivity Amplification Controller

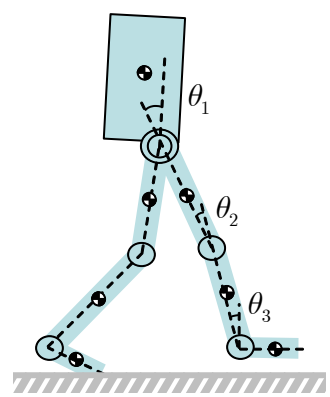

Fig. 4: Sagittal plane representation of BLEEX in the single stance phase (the human pilot is not shown).

In mixed control, position control in used for the stance leg and a positive feedback sensitivity amplification controller is used for the swing leg. Compared with the torso, where the unknown and frequently changing payload is located, the swing leg is easier to model accurately. The BLEEX swing leg is modeled as a 3 DOF serial link mechanism in the sagittal plane shown in Fig. 4. The dynamics of BLEEX can be written in the general form as:

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + P(\theta) = T + d \tag{6}$$

where $\theta = [\theta_1 \;\; \theta_2 \;\; \theta_3]^T$ and $T = [T_1 \;\; T_2 \; T_3]^T$.

M is a 3×3 inertia matrix and is a function of θ. $C(\theta,\dot{\theta})$ is a centripetal and Coriolis matrix and is a function of α and $\dot{\theta}$. P is a 3×1 vector of gravitational torques and is a function of θ only. T is the 3×1 actuator torque vector. d is the effective 3×1 torque vector imposed by the pilot on BLEEX at various locations. According to (5), we choose the controller to be the inverse of the BLEEX swing leg dynamics scaled by $\left(1-\alpha^{-1}\right)$, where α is the sensitivity amplification gain.

$$T = \hat{P}(\theta) + \left(1-\alpha^{-1}\right)\left[\hat{M}(\theta)\ddot{\theta} + \hat{C}(\theta,\dot{\theta})\dot{\theta}\right] \tag{7}$$

$\hat{C}(\theta,\dot{\theta})$, $\hat{P}(\theta)$ and $\hat{M}(\theta)$ are the estimates of the Coriolis matrix, gravity vector, and the inertia matrix respectively for (6) based on our model of the system. Substituting T from (7) into (6) yields,

$$\begin{aligned} &M(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + P(\theta) = \\ &\hat{P}(\theta) + \left(1-\alpha^{-1}\right)\left[\hat{M}(\theta)\ddot{\theta} + \hat{C}(\theta,\dot{\theta})\dot{\theta}\right] + d \end{aligned} \tag{8}$$

In the limit when $M(\theta) = \hat{M}(\theta)$, $C(\theta,\dot{\theta}) = \hat{C}(\theta,\dot{\theta})$, $P(\theta) = \hat{P}(\theta)$, and α is sufficiently large, d will approach zero, meaning the pilot can swing the leg as if BLEEX did not exist.

Stance phase: position control

Stance phase position control of the exoskeleton is motivated through a 1 DOF example shown in Fig. 5. This figure schematically depicts the master (a human leg) interacting with the slave (a 1 DOF exoskeleton leg in the stance configuration). The exoskeleton leg is shown as a rigid link pivoting about an ankle joint and powered by a single actuator that generates a torque T_{act}. The interaction between human leg and the exoskeleton leg in this example is interpreted as a spring-damper connection. This interaction generates an equivalent torque d about pivot joint.

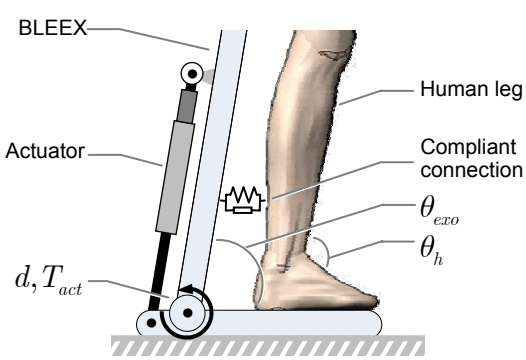

Fig. 5: 1-DOF master-slave schematic with a representation of the compliant human leg connection to BLEEX.

Fig. 6 shows the control block diagram of Fig. 5, where G represents the transfer function from the actuator torque T_{act} to the exoskeleton angular velocity v. C is the exoskeleton controller. The sensitivity transfer function, S (upper case), maps the equivalent interaction torque d onto the exoskeleton angular velocity v. The human-machine interaction torque, d, is a function of H, the interaction dynamics between the pilot and the exoskeleton, and the kinematics of the pilot limb and exoskeleton leg (e.g., velocity, position, or a combination thereof). In Fig. 3, H represents human dynamics. Note that because the human and the exoskeleton are tightly connected, human joint velocities are exactly same as exoskeleton joint velocities. In contrast, for stance control, as will be explained in following paragraphs, the connection between the human and exoskeleton needs to be compliant. θ_h and θ_{exo} (i.e. θ_e) are different and this difference is the input to our controller. Lower case s is used to represent the Laplace operator.

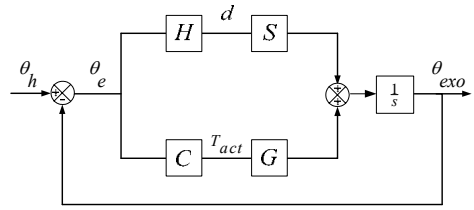

Fig. 6: Block diagram of 1 DOF position control.

The goal is to design a controller such that small θ_e can be achieved, i.e. BLEEX can track the human's motion. Notice that $d = H\theta_e$; small θ_e actually means small d. Therefore, BLEEX can track the human's motion without the human feeling an interaction force. The design specification is given by (9)

$$\left|\frac{\theta_{exo}}{\theta_h}\right| = \left|\frac{SH+GC}{s+SH+GC}\right| \approx 1 \qquad \forall\omega \in (0,\, \omega_0) \tag{9}$$

The controller is designed as a proportional controller by (10).

$$T_{act} = K(\theta_h - \theta_{exo}). \tag{10}$$

Implementation of position control

Master-slave position control is implemented for the stance leg, which is a multi-degree of freedom system. Here the master trajectories are the human joint angles (hip, knee, and ankle) and the slaves are the corresponding BLEEX joint angles. A proportional controller is used on each joint to cause the BLEEX joint angles to track human joint angles.

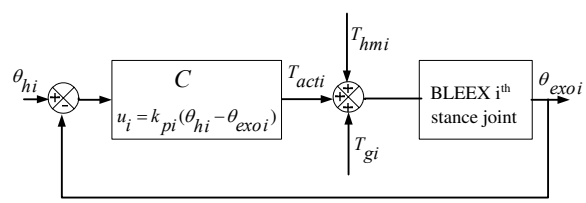

Fig. 7: Position control block diagram for ith joint.

The closed loop block diagram for each stance leg joint is shown in Fig. 7. θ_{hi} is ith human joint angle and $\theta_{exo\,i}$ is BLEEX ith joint angle. The actuator dynamics do not appear in the closed loop block diagram explicitly. The torques exerted on BLEEX include equivalent human machine interaction torque T_{hmi} (corresponding to d in Fig. 6), actuator torque T_{acti}, and gravity torque T_{gi}. In this control loop, θ_{hi} serves as

desired value and $\theta_{exo\,i}$ as measured value. The goal of the proportional controller is to make the error between the two joint angles as small as possible. Our controller is designed as:

$$u_i = k_{pi}(\theta_{hi} - \theta_{exo\,i}), \tag{11}$$

where u_i is the valve voltage for i[th] joint. Comparing with Fig. 6, human impedance H has been omitted in this block diagram. Also, human sensitivity S and BLEEX dynamics G are expressed in term of the BLEEX i[th] stance joint.

BLEEX is a multi-degree freedom system and the exact dynamic model is correspondingly complicated. In addition, the human-BLEEX interface is not a linear spring-damper system and it is not easy to model. As is done in many complicated nonlinear systems (especially in bipedal robots), position control is used to reduce the importance of a precise system model. The optimum k_{pi} is obtained though experimentation. A benefit of using this controller is that the computation time is greatly reduced because the position control calculations for a three DOF stance leg are significantly simpler than the three DOF stance leg inverse dynamics computations used in sensitivity amplification controller.

The success of this simple control scheme owes much to the considerations made in the mechanical design. An important principle of BLEEX design is that it should not impede the wearer's movement. Applying this principle to position control, it means that if the human wants to move, she should be able to move to her desired position easily, thus creating a detectable BLEEX-human desired joint angle difference to servo. How easily the wearer can move relative to BLEEX depends on the connection between the human and BLEEX and how well the controller tracks.

A 1 DOF mechanism is shown in Fig. 8 to illustrate how the contact between the master (human) and slave (BLEEX) influences the motion of the master. The foot is on ground and not moving. Only the shank is rotating about the ankle. For Fig. 8-a, there is no constraint between the master and slave. If the master wants to move, it simply moves to a new position. The position controller will cause the slave to follow the master without impeding the master's motion. However, for the mechanism shown in Fig. 8-b the master and slave are bound together. If master wants to move, it needs to move not only itself, but also the slave. Since they are bound together, the joint angle error between the master and slave is zero and the output of the controller is zero. Thus, position control with a rigid connection between master and slave impedes the motion of the master.

As described earlier, the human and BLEEX are connected in two locations: the torso and foot. Similar to Fig. 8-b, if the human torso is rigidly connected with the BLEEX torso, and the human attempts to lean forward, backward, or squat without moving her foot, then the human will be unable to generate an angle difference with BLEEX joints and the position controller will impede the human's motion. Thus, a flexible harness on the torso is necessary.

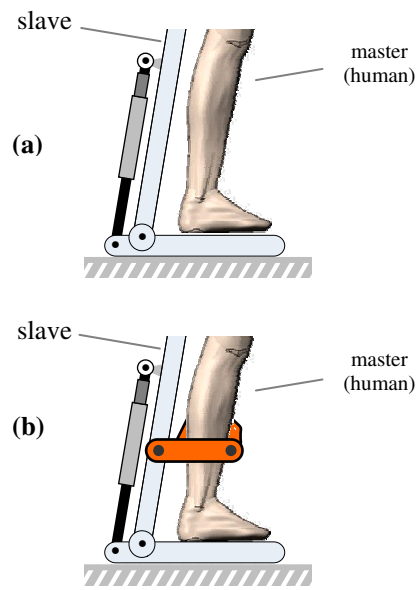

Fig. 8: 1-DOF mechanism master-slave conceptual representation with no physical connection between the human and machine (a) and with a rigid physical connection (b).

The connection between BLEEX and the human is illustrated in Fig. 9. The interface is illustrated as multiple spring-damper structures between BLEEX and the human. In reality, the foot attachment consists of a flexible binding and strap mechanism and the torso connection is a compliant backpack-like harness. There are no mechanical connections to the human on the shank and thigh, however the spring-damper structures in Fig. 9 are shown as a representation of potential voluntary intermittent contact between the human and BLEEX. Relative to BLEEX, the torso connection gives the human freedom in both the horizontal and vertical directions. In addition, our foot fixture is designed such that the human can rotate her toe or heel 15 degrees relative to BLEEX foot. This semi-rigid foot connection is also useful in the toe-off and heel-strike stages of the gait cycle.

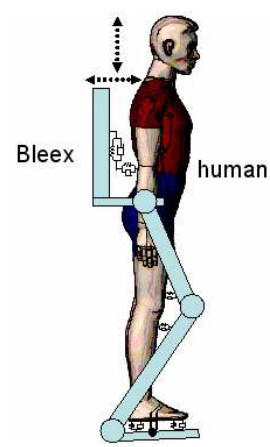

Fig. 9: Illustration of flexible contact on torso.

Besides the contact issue, another aspect that needs consideration is matching the geometry between the human and BLEEX. BLEEX is designed such that its thigh and shank length can be adjusted within a certain range (5%-95% percentile U.S. Army Male [14,15]). Even so, the human link

length and BLEEX link length are not guaranteed to be equal because of the discrete steps in the length adjustment mechanism. With master-slave control used on the stance leg, when the human squats, stands up, or leans back and forth, the length mismatch causes the distance between human and BLEEX torso to change. The relative position between the human and BLEEX is not that important as long as this position difference does not cause BLEEX to exert an uncomfortable force on the human. When a flexible harness is used, the distance change between the human and BLEEX torso in the horizontal direction is not problematic as long as the BLEEX CG is within the area of the BLEEX foot and the harness is not too tight. In the vertical direction, to ensure the BLEEX harness is not too tight in any particular human posture we need to loosen the harness such that when the human stands straight, this harness can be lifted off the human' shoulders by approximately 3~6 cm. To prevent the loose harness from impeding the human, the BLEEX controller must be tuned to respond quickly enough that the human cannot overtake the slack in the harness during rapid maneuvers.

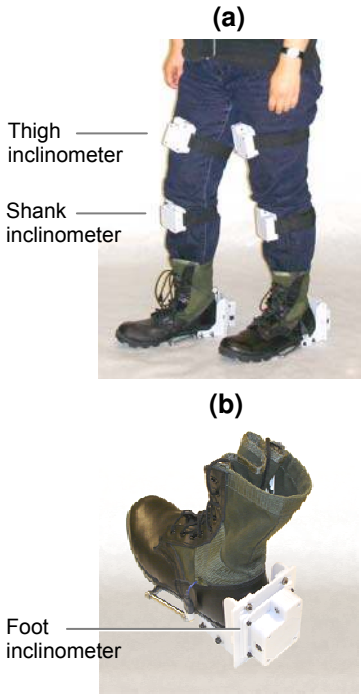

Fig. 10: Inclinometers used to measure joint angles of human on shank and thigh (a), and foot (b).

The sensors used to measure joint angles are encoders on BLEEX and inclinometers on the human limbs and torso. An encoder is used on each BLEEX joint to directly measure joint angles in the sagittal plane. BLEEX has two encoders on the ankles, two on the knees, and two on the hips. The human wears inclinometers to measure link angle relative to gravity. In total, seven inclinometers are used with two inclinometers on the feet, two on the shanks, two on the thighs, and one on the torso. Human joint angles are obtained by subtracting the angles between the corresponding proximal and distal links on the human body. Inclinometers were chosen to measure human angles because they are easy to attach to the human and they do not require precise relative alignment between the human's limbs. The mounting positions of inclinometers and encoders are illustrated in Fig. 10. Elastic straps are used to fasten the inclinometers on the human legs. Since the human foot can move a little relative to the BLEEX foot and tracking this small movement is crucial in the toe-off and heel-strike stages, inclinometers on the human feet are necessary.

In our initial testing, position control was applied to all joints for the entire walking gait cycle (no positive feedback control). It was immediately apparent that the technique was not successful for the swing leg of the single support phase of walking (one foot on the ground). With position control, if the human does not move her torso, then the master-slave controller keeps the BLEEX torso still. In this case, the human torso and BLEEX torso can be thought of as rigidly bound together. The small freedom of movement remaining in the human toe and heel attachment mechanism is not sufficient to allow the human to lift and swing her leg naturally. Thus, with the master-slave controller servoing these angle differences, the overall motion of the human and BLEEX was also unnatural and consequently uncomfortable for the human. For this reason we decided to combine master-salve control with the sensitivity amplification controller.

Transitioning between controllers

In the sensitivity amplification controller method proposed in our previous publications, the walking gait cycle is divided into three phases: single support, double support, and double support with one redundancy. The dynamic model is built based on these three phases [1,19]. However, in mixed control, the BLEEX model is based on each individual leg, instead of the status of both legs. Each leg state is decided independently and the corresponding control is implemented.

There are four possibilities for the state of each leg:

Stance:	the leg is standing on ground
Swing:	the leg is off the ground
Heel-strike:	the leg is stepping down to ground
Toe-off:	the leg is lifting off the ground

To decide which state each leg is in, two sets of digital pressure activated footswitches are used to provide information about the foot status of each leg. The BLEEX footswitch (shown in Fig. 11-a) is located between the BLEEX foot and ground. When the BLEEX foot is on ground, the BLEEX footswitch is on. The human footswitch (Fig. 11-b) is located inside the human boot like a shoe insole to detect whether the human is attempting to lift her foot. If the human wants to lift her foot, her heel is able to lift up a little inside the boot and this causes the human footswitch to turn off.

The controller records the foot switch status and keeps track of both the current sample value and the previous sample value. The leg status is decided according to these previous and current footswitch signals. If the previous BLEEX footswitch or human footswitch were off, and currently the BLEEX footswitch and human footswitch are on, then that leg is in the heel-strike mode. If previously both the human footswitch and BLEEX footswitch were on and currently human footswitch or BLEEX footswitch is off (i.e. the human wants to lift up), then that leg is in toe-off mode. If previously the BLEEX and human footswitch were on and currently BLEEX and human footswitch are on, then the leg is in stance mode. If previously the BLEEX or human footswitch were off and currently the BLEEX or human footswitch are off, then the leg is in the swing mode.

(a) **(b)**

Fig. 11: **(a)** BLEEX footswitch (between BLEEX and ground)
(b) Human footswitch (between BLEEX and human)

Heel-strike transition

When stepping down, each joint controller on the leg changes from sensitivity amplification based force control to position control. To prevent the control signal (valve voltage) from undergoing a sudden change, each joint position control gain K gradually changes from a small value, K_s, to the optimum experiment value k_p. Currently this is implemented with a profile function. The transition of the gain is finished in Δt sec. and the current experimental value of Δt is 1 second. This profile function was determined to be most comfortable for the human through experimentation.

Toe-off transition

When lifting off ground, each joint controller on the leg changes from position control to force control. Again, to prevent the control signal from undergoing a sudden change, the implemented actuator torque T in (10) is set to T_{start} (i.e. the actual actuator torques at the beginning of transition), and gradually change to the calculated value T from (7). As a cost of the smooth transition, the required torque for force control is not completely applied and the human needs to provide extra energy to compensate. Currently this is also implemented with a profile function. The transition of the implemented actuator torque T is finished in Δt sec. and the current experimental value of Δt is 0.4 seconds.

In both heel-strike and stance mode, the same position control algorithm is implemented; only the proportional gain, K changes. Similarly, in both toe-off mode and swing mode, the same force control is implemented. Only the applied actuator torque, T, changes. For faster walking, the fixed minimum transition period, Δt, will not cause instability but the human will need to provide more energy to achieve the desired motion and speed. Compared with load relief, the extra human energy expenditure was small and considered worthwhile by test subjects. Future work includes adding adaptation algorithms to adjust the two Δt values in response to the walking speed and testing different frequency-domain filtering approaches.

SAFETY CONSIDERATIONS

Because the human in close contact with the exoskeleton, safety is a very important issue. For the mixed control scheme, the inclinometers attached to the human are particularly vulnerable. If they were to fail or come loose from the human they could falsely report desired human joint angles that, if the controller were to track, would result in injury or discomfort. To prevent this, if an inclinometer reading error occurs, the controller tracking error $\theta_{hi} - \theta_{exo\,i}$ is software limited to be less than 15 degrees. In addition, if the controller cannot achieve desired tracking performance within a set time window, the system is shut down. These measures help to ensure the controller output will not cause BLEEX to overwhelm the human. Another example of the type of safety considerations that have been added for the mixed control scheme is to not allow both legs to be in swing simultaneously, which for mixed control would result in the payload being supported entirely by the human. These safety considerations were added in addition to the extensive safety systems in place on BLEEX for the original sensitivity amplification controller presented in [1].

CONCLUSION

With the mixed control method, a pilot can walk in BLEEX at 0.5 m/s (1.1 mph) with a payload of 18 kg (40 lbs) — tested in a laboratory setting on treadmill. This performance was inferior to the sensitivity amplification controller presented in [1]. Mixed control does offer other benefits in terms of robustness to changing payload dynamics. An additional problem encountered while testing mixed control was that the pilot needed to use a handrail to maintain lateral (side-to-side) balance. Once one leg was in swing, the whole pilot and BLEEX tended to fall toward the swing leg in the lateral plane. This was due in large part to the fact that abduction and adduction joints at the hip were not powered. Because the harness was loosened to improve the performance of the master-slave control mode, the pilot was unable to apply enough torque compensate for the lack of powered hip abduction and adduction. The pilot was able to provide a small balancing torque through the semi-rigid foot connection, but this was insufficient to provide lateral stability. We have demonstrated in [14] that powering the abduction-adduction joints at the hips eliminates the lateral control problem when walking with the sensitivity amplification controller and we conclude that it would also assist in lateral balance for the mixed control case.

The Berkeley Lower Extremity Exoskeleton (BLEEX) is not a typical servo-mechanism. It requires large sensitivity to pilot forces, which invalidates certain assumptions of the standard control design methodologies. One version of the controller, which we call a sensitivity amplification controller, uses the inverse dynamics of the exoskeleton as a positive feedback so that the loop gain for the exoskeleton approaches unity (slightly less than 1) [1]. The trade off is that this approach requires an accurate model of the system. As an alternative approach, mixed control is presented. In mixed control, master-slave control is used for the stance leg and a sensitivity amplification controller is used for the swing leg. In this way, it is not necessary to have a good dynamic model of the torso, which is hard to accurately obtain given that the payload can change. Laboratory walking experiments have been used to demonstrate the feasibility of this method. However, further development is still necessary to improve the inclinometer fastening method, resolve safety issues, and resolve balance issues.

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