A Survey of Current Exoskeletons and Their Control Architectures and Algorithms
(Draft 4.0)

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Abstract

In the simplest case, where the environment around a robotic system remains relatively fixed, controlling the dynamic interaction between the robot and the environment to achieve a specific physical objective is difficult. In the case where an operator effectively wears the robot, i.e., a robotic exoskeleton, and would like to move through unknown and dynamically evolving environments, the situation becomes very complicated; the robotic system needs to account for the dynamics of multiple fundamentally linked systems that are, for the most part, difficult to model. The goal of this document is to provide a survey of the literature on the design, modeling, and control of robotic exoskeletons and to highlight what we believe are several of the most promising currently existing approaches to the complicated goal of enabling dynamic yet safe interaction between operators, exoskeletons, and the environment. Where information was available, we summarize specific contributions related to actuation, power storage and generation, sensor type and distribution, mechanical architecture, as well as control system design for a number of different exoskeleton hardware systems. Included as part of this report are recommendations on what we see as helpful components as well as potentially problematic issues in current systems and control approaches.

1 Executive Summary

This paper surveys the following exoskeletons in detail:

- **BLEEX**: a “minimal-sensing” and aggressive model-based control design that has influenced many subsequent exoskeletons.
- **HAL**: an EMG controlled exoskeleton, emphasizing recognizing operator intent.
- **XoR**: a hybrid pneumatic/electric-motor system, emphasizing the value of using multiple actuator types. It also combines the use of brain signals and EMG for estimating operator intent.
- **Body Extender**: a fully actuated full body exoskeleton. This is the Iron Man option.
- **HLEE**: a nice and well presented example of a torque control approach.
- **IHMC MAE**: an SEA-based torque controlled exoskeleton, emphasizing the value of mixing passive mechanisms (local energy storage) and active actuation.
- **MIT Exoskeleton**: an attempt to take advantage of the passive dynamics of walking.
- **RoboKnee**: an example of a single-joint exoskeleton. Powerful single-joint or minimal exoskeletons are one way to enable operators to move fast and naturally, and greatly increase their strength.

Exoskeletons in a variety of categories are listed in the Appendix.

Based on our review, we have made the following conclusions:

- Most exoskeletons estimate user intent indirectly, from measurements of suit variables.
- Due to limitations in current sensory systems, it is difficult to sense user intent directly.
- As direct measurement of user intent is critical in dynamic, noisy environments, we recommend better fusion of low information density sensory data obtained from users with closed-loop control based on suit variables.
- In the longer term, we recommend investigation and development of more advanced human-exoskeleton sensing technology to capture user intent.

2 Introduction

This document summarizes what we have found to be several of the most relevant exoskeleton hardware systems and the associated controllers used to enable the hardware to effectively and safely interact with human operators. As we further elaborate, the different systems that we summarize range from the relatively simple and dramatically underactuated single joint mechanisms to extremely complex and fully actuated whole-body solutions. The controllers associated with these systems also ranged from solutions that implemented conceptually simple designs to those which made use of novel and more complex design techniques and/or relatively untried sensing and actuation technologies.

While this document does try to provide a relatively wide overview of existing exoskeleton technology, we did focus our efforts in this report on hardware systems meant to provide power augmentation and magnification as opposed the somewhat larger subset of exoskeletons designed primarily for rehabilitation. This choice was made relative to both hardware as well as control system design considerations. Exoskeletons designed for rehabilitation are not typically designed as stand-alone systems and are generally limited in the scope of operational modes in which they are capable of reliably providing assistance. The hardware designed for athletic operators and extreme tasks will need to be high-powered with a power source that is capable of being carried such that the suit is a completely stand alone unit.
and will need to run a control system that is capable of providing transparent support to
the operator in a large variety of operational scenarios.

To this end, the hardware systems that we chose to include summaries of in this document
were the BLEEX, HAL, XoR, Body Extender, Hydraulic Lower Extremity, IHMC Mobility
Assist, MIT, and RoboKnee exoskeletons. The different systems cover many of the possible
choices of actuation strategies, ranging from electric motors, to hydraulics, to pneumatics,
and combinations thereof. Several of the systems used novel transmission strategies as
well, focusing on both efficient as well as high-fidelity force control implementations. The
transmission strategies included standard hydraulic systems, hydraulic systems with actively
controlled bypass valves, ball-screw mechanisms that include series elastic components, as
well as pneumatically actuated pulley-tendon and belt-drive mechanisms.

In terms of sensing and control technologies, the different exoskeletons covered in this
report employed a wide variety of the spectrum of available options. Sensors were used
to measure everything from standard information, like angular displacement of the hard-
ware system’s joints, to more novel information, like muscle activity of the user using EMG
technology. Sensor information was used as the basis for a variety of different closed and
open-loop control system designs, ranging from straight-forward force control and trajec-
tory following to novel approaches of fully actuated feedback linearization and sensitivity
amplification strategies.

Each of these component technologies are reviewed as they relate to the hardware systems
discussed in this report. Recommendations on what we feel are the best approaches in these
reviews are also provided. We provide a summary of these recommendations at the end of
this document.

3 BLEEX

The Berkeley lower extremity exoskeleton (BLEEX) is an anthropomorphic, powered ex-
oskeleton designed for human strength augmentation. It is described as the first field-
operational robotic system to allow its operator to carry significant loads over unstructured
terrain without external power [3].

The BLEEX system includes two 7 DOF, three-segment legs with thigh, shank, and
foot links, on-board power supply, and a backpack-like frame. The human wearer is rigidly
connected at the feet and torso such that the frame shelters the user by transferring load
forces to the ground. The leg segments are connected by rotational joints including 3 DOF
(2 actuated) at the hip, 1 DOF (actuated) at each knee, and 3 DOF (1 actuated f/e in
sagittal plane; 2 passive) at the ankles. Joint angles, torque, and power requirements are
determined from human motion analysis based on a 75-kg human walking on flat ground at
roughly 1.3 m/s (the average military male’s maximum reported joint limits are also used to
derive joint range of motion targets). During design, joint motion was intended to be slightly
less than the maximum human range of motion for safety; however, some joint ranges had
to be reduced to avoid (mechanical) singularities.

Due to its high power to weight ratio (twice that of electric motors), BLEEX uses a
hydraulic actuation system. An on-board internal combustion engine provides both electric
and hydraulic power. The joints are driven by commercial small bore (2cm) dual action
hydraulic actuators operating at 6.9 MPa. Though the operating pressure is relatively low, the hydraulic actuation system exhibits significant pressures losses across servo valves when less pressure is required than this system pressure. Table 1 provides details regarding the range of motion and torque capabilities of BLEEX’s joints. As reported in [3], BLEEX requires 1,143 W for walking relative to 165 W for human walking (14% efficient compared to a human of the same size). Altogether the suit needs 2.27 kW of hydraulic power and 220 W of electric power to accommodate climbing (540 W) and remaining electrical loads including 240 W to power the second stages on servo vales.

3.0.1 Control

The BLEEX team has successfully implemented both sensitivity amplification [2] and a hybrid assistive control scheme [1] that switches (based on gait phase) between sensitivity amplification and a position control regulating desired torque. This section focuses on sensitivity amplification, as the hybrid assistive strategy did not perform as well in walking trials.

In its sensitivity amplification implementation, BLEEX controllers attempt to minimize interaction forces between the human pilot and the exoskeleton. However, the BLEEX team
Table 1: BLEEX joint range of motion (ROM) is near anthropomorphic. The max torques are designed to meet the torque / power requirements of similarly sized human walking at 1.3 m/s [3].

<table>
<thead>
<tr>
<th>Joint Type</th>
<th>BLEEX ROM</th>
<th>human max torque &amp; power</th>
<th>BLEEX max torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle flexion / extension</td>
<td>±45°</td>
<td>−120 N-m; 250 W</td>
<td>−200/155 N-m</td>
</tr>
<tr>
<td>Ankle abduction / adduction</td>
<td>±20°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Knee flexion</td>
<td>121°</td>
<td>−35/60 N-m; −150/50 W</td>
<td>−100/140 N-m</td>
</tr>
<tr>
<td>Hip flexion / extension</td>
<td>±121°/10°</td>
<td>−80/60 N-m; −60/115 W</td>
<td>−150/130 N-m</td>
</tr>
<tr>
<td>Hip abduction / adduction</td>
<td>±16°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>total rotation external</td>
<td>35°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>total rotation internal</td>
<td>35°</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

makes a point to avoid direct measurements of the interaction force between the human and the exoskeleton suit. They highlight difficulties in properly outfitting humans with necessary sensing equipment and challenges in modeling the interaction between the human and exoskeleton (e.g., non-rigid, non-fixed contact points). Instead, the team develops controllers based on an inverse dynamic model (in the sagittal plane) of only the exoskeleton.

The BLEEX sensitivity amplification control strategy models the torque applied by the human pilot on the exoskeleton as \( d \) (assuming no outside disturbances). Neglecting gravity, the exoskeleton angular velocity is modeled as

\[
v = Gr + Sd,\]

where \( G \) is the transfer function from actuator inputs \((G)\) is the exoskeleton’s dynamics).
r is the actuator input, and S is the sensitivity or transfer function from human torque to exoskeleton angular velocity.

The goal is to maximize sensitivity to \( d \) without direct measurement. Sensitivity amplification accomplishes this by creating a feedback loop from a controller, \( C \), acting only on exoskeleton variables. A new sensitivity equation,

\[
S_{\text{new}} = \frac{v}{d} = \frac{S}{1 + G C},
\]

is maximized by applying positive feedback. To achieve a large sensitivity, BLEEX uses \( C = (1 - \alpha^{-1})G^{-1} \) so that \( \alpha \) provides a direct (scalar) amplification factor. A low-pass filter is often added to the \( C \) term in order to damp out high frequency dynamics of the exoskeleton, which are not captured in these models. Note that the controller depends on an inverse dynamic model of the exoskeleton, \( G^{-1} \). Since the model is hybrid, these dynamics switch according to gait phases (single support, double support, stance). BLEEX detects these transitions using foot sensors. Assuming the single leg support dynamics are in the form,

\[
M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + V(\theta) = T + d, \tag{1}
\]

where \( T \) is a vector of actuator torques and \( M(\theta) \), \( C(\theta, \dot{\theta}) \), and \( V(\theta) \) are the mass, Coriolis, and gravity terms (respectively), the BLEEX control torque would be

\[
T = V(\theta) + (1 - \alpha^{-1})[M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta}]. \tag{2}
\]

The user must provide the first torque component as the exoskeleton has no actuator acting between the foot and the ground (the system is underactuated).

As a note, positive feedback is normally avoided in control design because it amplifies disturbances. In the case of BLEEX, designers sacrifice disturbance rejection to maximize the response of the suit to its wearer. Users must therefore take action to stabilize and balance out disturbances.
For sensing, BLEEX uses information from 8 encoders and 16 accelerometers to determine angle, angular velocity, and angular acceleration of eight actuated joints. It includes a foot switch and load distribution sensor at each foot. Eight single axis force sensors provide measurements required to perform low level force control at each actuator. An inclinometer indicates the orientation of the backpack relative to gravity. Using this sensitivity amplification control scheme, BLEEX has achieved successful walking at 1.3 m/s with a 34kg payload [2].

3.1 Assessment and Recommendations

Sensitivity amplification is a current best-in-class control strategy. The exoskeleton shadows the user and uses exoskeleton data for joint angle, velocity, and acceleration and the exoskeleton model to minimize torques experienced by the human torque. The process and hardware are relatively simple yet effective. However, the approach has several significant disadvantages including heavy reliance on an accurate exoskeleton model and the fact that sensitivity amplification will amplify disturbances. Note that in highly dynamic, contact-rich environments this latter point is critical, as a sensitivity amplification will amplify forces acting on the suit and the operator will have to re-act to compensate. The only way to compensate for or resist external forces in this setting is to filter them out, which would be extremely challenging unless additional sensory equipment is provided. As one possibility, a sensitivity optimization approach may be paired with sEMG (surface electromyography) data to estimate user intent and provide such a filter. Note this type of implementation would present its own challenges considering limitations in sensing and calibration of current EMG systems. Section [11] discusses new flexible sensory arrays and other technologies and strategies to capture / filter based on user intent.

References


The figures in this section were obtained from [2]. Materials presented are based on the references above.

4  HAL

The hybrid assistive limb (HAL) exoskeleton is developed by the University of Tsukuba and Cyberdyne for human strength augmentation and as an assistive gait device in rehabilitation. Although several prototypes have been developed, this section focuses on the most recent HAL-5 model (specifically the non-clinical type, HAL-5 Type-B). Though HAL-5 is a full body exoskeleton, only hip, knee joints, and ankle are actuated in the sagittal plane. The exoskeleton uses DC motors with harmonic drives at hip, knee, ankle joints (in some models the ankle joints act as passive springs). HAL weighs 23kg and includes an on-board AC100V battery as the power source, which is designed to support maximum velocity human walking and standing torque requirements. The battery allows for 160 min of continuous operation and enables the exoskeleton to lift up to 70kg [5].

Human operators attach to HAL at the waist with a belt, and at the calf and thigh using harnesses. HAL’s frame does not transfer load to the ground. Instead, HAL adjusts hip, knee and ankle torques to amplify its operator’s torque. The exoskeleton’s sensory system includes bioelectric sensing (including sEMG), angular sensors, acceleration sensors, and center of pressure / center of gravity (COP/COG) sensors. COP/COG sensing is provided through shoes with ground reaction force sensors. The joint measurements are provided by potentiometers. In at least one version of HAL the bioelectric data comes from sEMG sensors installed below the operator’s hip and above the knee (on both front and back). An IMU installed in HAL’s backpack is used to estimate torso pose.
4.0.1 Control

HAL has two types of control systems designed for different application domains. For gait assistance and rehabilitation, HAL uses an autonomous control system that carries the user through predefined gait trajectories by controlling knee and hip joints (the ankles behave as passive springs). Gait phase intention is estimated from COP/COG sensors. The exoskeleton drives the wearer to follow pre-recorded desired joint patterns.

The second control strategy, a model-based approach for human strength augmentation, estimates human intention from sEMG activity and provides power to augment torque provided by the operator. A relatively autonomous torque assist strategy in [3] recognizes user intention to take a step by thresholding sEMG data. The approach provides a knee torque response including an assistive torque component, a viscous damping component that reduces high velocity motion for safety, and a gravity compensation torque.

In [1], an impedance control strategy controls the viscoelastic properties of HAL’s knee joint from a musculoskeletal model of operator’s limb moving in concert with the exoskeleton. The controller uses sEMG sensor data to estimate muscle torque based on the difference between flexor and extensor muscle activities. The authors note the sEMG model requires significant calibration effort. Viscoelastic torques are computed according to

\[ \tau_{a,i} = \alpha_i (-D_i \dot{\theta}_i - K_i \theta_i), \]

based on a variable gain set by \( \alpha_i \). The net knee actuator torque is

\[ \tau_i = \tau_{a,i} + \tau_\mu + \tau_c. \]

The torque includes a \( \tau_c \) term compensating for mechanical (actuator) impedance and \( \tau_\mu \), a scaled version of the human torque (as estimated from sEMG data). The \( K_i \) and \( D_i \) terms in \( \tau_{a,i} \) are viscoelastic parameters (based on the operator’s muscles) in the human-exoskeleton model. These parameters are estimated on-line using a weighted least-squares method. In this case, the angular velocity data required for the impedance controller is estimated from a state observer.

While experiments in [1] only consider leg swing-up and swing-down, a similar control approach in [4] switches the dynamics based controller to compensate for swing and stance phases in walking gait. In this case, the gait transitions are detected by thresholding foot sensors and required angular velocity (and acceleration) data are determined by numerically differentiating angular encoders.
4.1 Assessment and Recommendations

Compared to sensitivity amplification methods, HAL’s use of EMG data allows it to estimate intention without amplifying external disturbances. While direct sensing of user intention is ideal for noisy, contract-rich environments, sEMG data is extremely difficult to work with due to high filtering and calibration requirements. A hybrid strategy which uses sensitivity amplification and sEMG data (possibly thresholded) to filter user intention could prove effective. Additionally, Section 11 mentions new capabilities in nano-fabrication and MEMs technologies that have produced new high-density, wearable sensing arrays. These and similarly advanced sensing technology may facilitate direct measurement of interaction forces (i.e. estimating pressure / force and exoskeleton contact locations), which could potentially filter external disturbances from user generated input to estimate intent.

References


The figures in this section were obtained from [1, 5]. Materials presented are based on the references above.

5 XoR

The XoR is a prototype light-weight, lower-body exoskeleton that uses a hybrid pneumatic-electric drive system that reduces weight while providing precise torque control, backdrivability, and a desirable force / velocity profile. The exoskeleton is designed to serve in rehabilitation settings to augment operators’ strength and assist with postural control for persons with disabilities.

The XoR weighs 30kg and includes 10 DOF with 6 active joints (flexion / extension of hip, knee, and ankles) and 6 passive (hip abduction/adduction joints, hip rotation, and ankle
adduction/abduction). The active joints are powered by hybrid actuators comprised of an air muscle and an electric motor. The hybrid actuation scheme uses a unilateral air muscle layout to compensate for gravity and bilateral electric motors with a relatively small gear ratio (57.5) to serve as the dynamic compensator.

The actuation scheme is complementary in that the electric motors have a quick response time and produce high peak torque for short amounts of time, while air muscles have a delayed response (true of pneumatic systems in general due to the compressibility of air) with better power density and sustained torque. The hybrid drive system sums the two to develop a desired torque profile that achieves the benefits of both and reduces weight and motor size. The system offers high torque control with negligible stick-slip and backdrivability.

A challenge in using air muscles is that force reduces quadratically as a function of contraction. For instance, at 30% contraction, the force produced by FESTO rubber air muscles vanishes. To address the issue, XoR’s air muscles are strategically placed to generate forces in desired configurations.

In implementation, the XoR uses rubber air muscles (MDSP-40) connected to pulleys via tendons and to electro-pneumatic regulators in the backpack (a constant pressure and cam system is being tested to reduce weight required for backpack air valves). The electric actuator is a geared, 200W brushless DC motor (Mason EC powermax 30) rated at 4.7 A, which transmits power to joints through a belt and pulley system with a 57.5 gear ratio. The motor is backdrivable with 0.12 Nm output torque and up to 34.5 Nm (for short duration) at every joint. The design yields a relatively high range of motion (up to 120 degrees) with
a 150 Nm load capacity. However, experiments reveal the need for bi-directional pneumatic actuation at hip joints.

For sensing, XoR is equipped with **rotary encoders** at joints, an **IMU** in the backpack, **load cells** in the feet, and is networked to servers capable of providing **EMG**, **NIRS** (near-infrared spectroscopy), and **EEG** (electroencephalogram) data. A control PC running at 1 KHz, pulse counter, amplifiers, Digital IO are external and so not included in the weight of the unit. Human operators are outfitted with a **goniometer**.

### 5.0.1 Control

The XoR control strategy applied in [2] has two main components. First, a proportional-derivative (PD) feedback controller tracks desired joint angles and angular velocities that correspond to the state of the exoskeleton required to assist the human operator. To obtain this state (specifying the desired joint angles / velocities), the controller simultaneously measures the joint angle trajectories of the human user (goniometer) and of the robot (encoders), and uses canonical correlation analysis (CCA) to extract latent variables in the kinematic relationship between the two.

To avoid relying on high gain feedback, XoR incorporates user intent through EMG data. The controller rectifies and low pass filters (10 Hz cut-off) data measured in the pilot’s quadriceps femoris, tensor fasciae latae, gluteus medius, and tibialis anterior. It sets desired joint angles and velocities, \( \mathbf{x} = (\theta, \dot{\theta}) \), from the EMG data, \( \mathbf{u} = (EMG_1, \ldots, EMG_n) \), using a linear prediction model,

\[
\mathbf{x}(k + 1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}\mathbf{u}(k),
\]
The controller uses the angular measurements required to perform CCA and EMG data to derive the model’s $A$ and $B$ terms. The predicted state from EMG model provides the desired input to yet another PD controller:

$$
\tau_i = K_p(\theta^d_i - \theta_i) + K_d(\dot{\theta}^d_i - \dot{\theta}_i),
$$

with gains of $K_p = 1000$ and $K_d = 100$.

In hip tracking experiments, the team found EMG data to be helpful. When using EMG signals, XoR achieved a mean squared error of $1.8E^{-3}$. Without the EMG data, the mean squared error increased to 2.1. Additional experiments confirm the air muscles can effectively perform gravity compensation when used in conjunction with electric actuators (to correct for torque errors induced by inaccuracies in the model mapping position to torque in air muscles).

### 5.1 Assessment and Recommendations

The XoR prototype uses a promising hybrid actuation scheme to achieve both fast peak torque response and higher sustained torque while remaining lightweight. It tracks human motion with feedback from a goniometer and feedforward control provided by EMG data. These human intention / sensing modalities are both difficult to implement due to noise and calibration issues. However, capturing the user intent is important, especially in the presence of external disturbances. If the sensory system were improved (see the discussion in Section 11), this exoskeleton design could be highly effective.

### References


The figures in this section were obtained from [1, 2]. Materials presented are based on the references above.
6 Body Extender

The Body Extender is one of the few existing full-body exoskeletons. The Body Extender’s main objective is to increase the forceful interaction capabilities, specifically the heavy load handling capabilities, of an operator in difficult and unknown environments. The overall suit is composed of four robotic limbs with kinematics designed to be anthropomorphically similar. The suit contains twenty-two independently actuated degrees of freedom. Note that the Body Extender is the only fully actuated suit included in this report. The fully actuated design of the suit was chosen based on the fact that handling, or rather manipulating heavy objects requires forces and torques that far exceed human capabilities. Note also that having many actuated degrees of freedom means that fully actuated suits will be very heavy, and thus will require specialized controllers.

As a primary objective, the Body Extender aims to allow operators to use the hardware with minimal training. Thus, the system is designed so as not to require substantial modifications to human motor habits. The effective mass distribution of the suit, of special consideration in these heavy systems, is designed to be similar to that of an unloaded operator. Like most other strength augmentation exoskeletons, the Body Extender is intended to minimize resistive forces between the operator and suit, even when the suit is not loaded externally.

A picture of the Body Extender exoskeleton and its five main components, four limbs and a torso, is shown in Figure 1.

![The Body Extender](image1.png)

Figure 1: The Body Extender.
6.1 Actuator Specifications

Except for forearm pronosupination, each of the actuators in the Body Extender suit are driven by a linear actuator that is composed of an electrical motor, incremental encoder, ball screw, and angular contact ball bearings. The motors are frame-less DC torque controlled motors. The **peak torque of the motors is 7 Nm, with a maximum continuous torque of 6 Nm**. Each motor weighs 1.4 kg. The linear actuator assembly is able to supply 8000 N with a total weight of 2.4 kg.

Joints that have a small range of motion and low torque requirements use linear actuators in straightforward lever mechanism configurations. For degrees of freedom which require relatively large ranges of motion as well as torque, a motion conversion system transforms the linear actuator motion into rotational motion. The motion conversion unit consists of a pantograph, two metallic tendons, and an output pulley connected to the output link. A CAD drawing of the motion conversion unit is shown in Figure 2. There are two configurations of the motion conversion unit. The first has a maximum continuous output of 500 Nm and the second a maximum continuous output of 270 Nm. The two units weigh 6 kg and 5 kg respectively, and have mechanical efficiency of about 85%. The speed of the actuators is approximately 60 deg/s.

![Figure 2: CAD view of the internal components of the actuation module.](image)

6.2 Exoskeleton Specifications

The Body Extender’s twenty-two actuated degrees of freedom include two arms, two legs, and a torso or central backpack unit. The arms have a servo-amplified degree of freedom for grasping heavy objects. Grasping forces are achieved using a force sensing trigger mechanism; the force is proportional to the force applied to the trigger.

The suit contains twenty-two incremental encoders that measure angular displacement of each of the electric motors. There are also **five six-axis force/torque sensors mounted at the five connecting points between the user and the device; two at the hands, two at the feet, and one on the trunk**. These sensors directly measure the forces and torques between the user and the suit. There are additionally two single axis force sensors integrated into the grippers that measure the force applied by the operator on the “gripper triggers,” as well as a **three axis accelerometer integrated into the backpack unit which estimates the trunk orientation**. Lastly, accelerometers are distributed throughout the system to monitor link dynamics, supporting overall equilibrium and internal stability during manipulation tasks.
The control software is distributed between a central processing unit and sixteen local units located throughout the system. The communication between processing units is handled using a high-speed field bus.

The system is powered using thirteen batteries in series, which provide a nominal voltage of 78 V. When the system is run in stand-alone mode, the batteries can provide eight hours of continuous work.

6.3 Control Specifications

The body extender control algorithm centers around a feedback linearization policy that depends on measuring the force between the operator and suit, knowing the contact state of the suit and environment, decoupling the control of each of the limbs for each other, and having each limb be fully actuated. The dynamics for each of the Body Extender limbs are written in standard form as

$$\mathbf{B}_i(q)\ddot{q} + \mathbf{C}_i(q, \dot{q})\dot{q} + \mathbf{G}_i(q) = \tau + \mathbf{J}_{iu}^T \mathbf{F}_s + \mathbf{J}_{ia}^T \mathbf{F}_a,$$  \hspace{1cm} (3)

where $i$ is an integer corresponding to a different limb, $\tau$ represents the actuator torques, $\mathbf{F}_s$ the measured forces between the operator and suit, and $\mathbf{F}_a$ the unmeasured contact forces on the suit. The $\mathbf{B}_i$, $\mathbf{C}_i$, and $\mathbf{G}_i$ terms represent the limb inertia, Coriolis and centrifugal, and gravitational torques.

The authors in [2] use a decoupling strategy in their controllers which enables the individual limbs in the Body Extender to be somewhat decoupled from each other. They claim that they accomplish this using the following model:

$$\mathbf{B}_i(q)\ddot{q} + \mathbf{C}_i(q, \dot{q})\dot{q} + \mathbf{G}_{iT}(q) = \tau + \mathbf{J}_{iu}^T \mathbf{F}_s + \mathbf{J}_{ia}^T \mathbf{F}_a - \mathbf{B}_{iT}q \dot{V}_T - \mathbf{C}_{iT}(q, \dot{q})V_T,$$  \hspace{1cm} (4)

where, $\mathbf{V}_T$ is the trunk velocity, $\mathbf{G}_{iT}$ the gravitational effect of the trunk on the limb, $\mathbf{B}_{iT}$ the inertia of the trunk acting on the limb, and $\mathbf{C}_{iT}$ the trunk Coriolis and centrifugal term. Note that $\mathbf{V}_T$ and $\dot{\mathbf{V}}_T$ are directly measured through the accelerometer and gyroscope in the trunk.

The feedback linearizing controller in operates under two fundamental assumptions and only appears to relate directly to the case of a single manipulator arm. The first assumption of the controller is that the mass and inertial properties of an object being manipulated are estimated online. The second is that the forces measured between the operator and suit can be modeled as

$$\mathbf{F}_s = \mathbf{M}_p \ddot{V}_e + \mathbf{G}_p,$$  \hspace{1cm} (5)

where $\mathbf{M}_p$ is an effective mass of the end effector, $\ddot{V}_e$ is the acceleration of the end effector, and $\mathbf{G}_p$ is an effective gravitational term. Note that the gravitational term is zero if the arm is not holding an external load. The importance of these two assumptions will be more clear after the analytical forms of the feedback linearizing controllers are introduced.

The dynamics of the arm when not manipulating a load are

$$\mathbf{B}(q)\ddot{q} + \mathbf{C}(q, \dot{q})\dot{q} + \mathbf{G}(q) = \tau.$$

The feedback linearizing controller for this case has the form

$$\tau = \mathbf{B}(q)(\ddot{q}_d + K_v^{-1}\dot{q} + K_p^{-1}q) + \mathbf{C}(q, \dot{q})\dot{q} + \mathbf{G}(q),$$
where \(-q = q_d - q\). The details are unclear in [2], but it appears that the authors either propose using predefined trajectories to define \(q_d\), \(q_d\), and \(q_d\), or use the assumption in (5) to determine these values. Equation (5) relates the measured force to the derivative of the end effector velocity \(\dot{V}_e\). This end effector velocity can then be related to the desired joint velocities using the analytical Jacobian transformation

\[ \ddot{q}_d = J(q)^{-1}(\dot{V}_e - \dot{J}(q, \dot{q})q). \]

The values for \(\dot{q}_d\) and \(q_d\) can then be found through integration. It is not clear how the authors explicitly decouple the human dynamics from the robot in this case.

In the case where the exoskeleton arm is manipulating a load, the feedback linearizing controller has the augmented form

\[ \tau = B(q)(\ddot{q}_d + K_v\dot{q} + K_pq) + C(q, \dot{q})q + G(q) - J^T(q)F_s - J^T(q)F_a. \]

The main difference in this case is that the controller here explicitly compensates for the measured human-robot interaction force \(F_s\), and the controller includes the un-sensed forces \(F_a\) which arise from the object being manipulated. The object interaction forces thus need to be estimated. The ability to estimate these forces is the first fundamental assumption on which the Body Extender’s control scheme relies. Because the point at which the manipulator arm and object are connected is assumed to be well known, and the arm is instrumented with inertial sensors, estimating the interaction forces of the manipulated object is assumed to be equivalent to estimating its inertial properties. As outlined in [2], this is accomplished using a standard regressor which uses the input and output of the feedback linearizing controller as the basis for the regression. The details of this process are left to [2].

### 6.4 Assessment and Recommendations

The Body Extender suit is one of the only fully-actuated upper and lower extremity exoskeletons available today. Clearly, for the task of handling extremely heavy objects, a fully actuated suit may be the best option, but, generally speaking, having the additional weight due to actuating every degree of freedom in the suit is not ideal when considering dynamic operation.

The controllers highlighted in [2] do present some novel components. For example, using a regressor to estimate unknown external forces may be an idea which is directly applicable to a variety of different projects. Note that in the case of the Body Extender, this regression is dependent on knowing the location of the external force relative to the suit, the manipulator end effectors. Thus, an extension of this idea, possibly using a larger distribution of sensors to measure external forces, is necessary to extend this approach more generally.

The way that the Body Extender control uses operator-robot measured interaction forces to generate desired trajectories around which a stabilizing controller is designed is generally an idea that we support. Note that, like any of the model-based control approaches outlined in the exoskeleton literature the feedback linearizing controller in this work is dependent on knowing the model of the robot hardware with a relatively high-level of fidelity.

In terms of the controlling of the overall suit, i.e., locomotion in addition to manipulation, it was difficult to find any papers that discussed more than upper-body single-arm control
of a manipulated object for the Body Extender hardware. The stated strategy of decoupling
the individual limbs from each other seems somewhat feasible, but is limited relative to
coordinated limb control.

The speed of the actuators (approximately 60 deg/s) is far too slow for dynamic human
movement.

The mechanical specifications as well as figures related to mechanical design for the Body
Extender system discussed in this section are based on and taken from [1]. The discussion
of the control system is based on work presented in [2].

References


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7 Hydraulic Lower Extremity Exoskeleton

The Hydraulic Lower Extremity Exoskeleton suit was originally developed for military uses,
specifically to allow operators to perform motions without incurring muscle fatigue. The
exoskeleton uses a new virtual joint torque control approach, which has been shown
to be effective for controlling human robot interaction in situations where the connections
between the users and hardware system are relatively unknown or can dramatically change
as a function of time.

Additionally, the main hardware design principle is focused on developing a suit that can
augment user power and yet move fast when necessary. The design team selected hydraulic
actuators because the weight of electric actuators on leg joints would make the system
difficult to move quickly. Hydraulic actuators have high power density relative to weight
and size and generally provide very high force outputs and low impedance. As a trade-off,
hydraulics have reduced accuracy in terms of force control and it is difficult to model their
nonlinear characteristics.

A picture of the Hydraulic Lower Extremity Exoskeleton is presented in Figure 3.

7.1 Actuator specifications

The Hydraulic Lower Extremity Exoskeleton’s actuators were designed based on human
walking data obtained at 4 km/h with a 45 kg load. Based on this data, the hydraulic
capacity system was designed to provide 2050 psi and 8 LPM. The individual actuators were
designed to be double acting at the hip and knee flexion(extension joints. They provide a
hip maximum thrust of 4 kN and knee maximum thrust of 4 kN. Each joint joint
includes three-way servo valves (M 200, Star-Hydraulic) to control rate and direction of
bi-directionality, and bypass valves to connect the pump path to tank path for fast, energy-
efficient motion during swing phases.
7.2 Exoskeleton Specifications

The Hydraulic Lower Extremity Exoskeleton includes four actively controlled joints in the sagittal plane, with powered knee and hip flexion/extension. The eight passive joints include one ab/adduction DOF for each hip and 3 DOF for each ankle.

The hydraulic system is composed of the four actuators and a hydraulic power unit, consisting of a pump, motor, temperature sensor, and various valves.

On-board sensors measure **joint angles**, **actuator forces**, and **ground reaction forces**. Three **absolute angular encoders** are incorporated at the hip, knee, and ankle pitch joints. In-line **load cells** are incorporated in each cylinder tube to measure actuator forces, and four single axis load cells are included in foot sensors to be used for gait phase detection.
7.3 Control Specifications

The control design principle for the Hydraulic Lower Extremity Exoskeleton is based on the concept that, for walking gaits, the **stance and swing controllers should be considered separately**. To this end, the control designers developed an active-passive control method called **Dual-Mode Control**. Active control is used during stance phases whereas the passive control is used to quickly and freely control the system’s legs during swing phases. Additionally, to handle the inherently discontinuous jumps in the command signals that occur in this dual mode abstraction, a smoothing method is used in conjunction with a pre-transition method that solves for the swing delay due to internal cylinder pressure. A diagram which highlights the different modes in this control strategy is in Figure 5.

Various components of the dual-mode control strategy, at the hardware level, are presented in Figure 6. This figure contains a **gait phase estimation block**, which uses the foot sensors to estimate the stance mode of the system, a **human intention block**, which uses
angular encoders and joint force sensors to estimate the motion of the operator, a **torque controller**, and a **gravity compensation** block. Note that these various components of the control system are used to support the general assumption of the dual mode controller, i.e., where, \( GP \) is the gait phase, \( GRF \) is the ground reaction force, and \( \delta \) is a threshold value. This equation explicitly states that an active torque will be applied for each leg during stance and that the legs are passive in their respective swing phases.

Like other controllers presented in this report, the dual mode control method in this section uses the fundamental assumption that it is difficult to measure the interaction forces between the user and hardware system directly as a primary design principle. To this end, the human-robot interaction force is assumed to be completely represented in terms of the joint torque applied by the operator in the hardware.

To calculate the active torque applied to the joints during the active mode control, the robot dynamics are considered independently from the operator, namely,

\[
T_a = M(q)\ddot{q} + C(q, \dot{q})\dot{q} + G(q),
\]

where \( T_a \) is the joint torque applied by the actuators, \( M(q) \) is the inertia matrix, \( C(q, \dot{q}) \) is the centripetal and Coriolis matrix, and \( G(q) \) is the gravitational torques. This equation neglects friction as well as other actuation dynamics.

Using the force sensors on the hydraulic actuators, the human-robot interaction torques can be approximated as

\[
\hat{T}_{hm} = M_n(q)\ddot{q} + C_n(q, \dot{q})\dot{q} + G_n(q) - \hat{T}_a,
\]

where \( M_n, C_n, \) and \( G_n \) are the nominal models of the true inertia, centripetal, and gravitational parameters and \( \hat{T}_a \) represents the measured actuator torques. The \( M_n(q)\ddot{q} + C_n(q, \dot{q})\dot{q} + G_n(q) \) portion of \( \hat{T}_{hr} \) represents the inverse dynamics component of the closed-loop control system. The overall joint torque controller, which combines compensation for operator intent as well as balancing of the suit under a gravitational load, is then written

\[
\tau_{active} = K(s)\hat{T}_{hm} + G_n(q),
\]

where \( K(s) = K_p + sK_d \), i.e., there is closed-loop PD control law operating on the error between the predicted robot dynamics and the measured joint torques. The block diagram for the active mode controller is shown in Figure 7. Note that \( G_a \) represents the dynamics of the system and \( G'_a \) the inverse dynamics model in Figure 7.

In the passive mode, which occurs during the swing phase, the leg of the human-robot system moves quickly and freely under using the passive inertial forces of the overall system. This is accomplished using bypass valves that connect the pump and tank paths to achieve mechanical back-drivability. The foot sensors trigger the bypass valves and to initiate the pass control mode.

The Hydraulic Lower Extremity Exoskeleton uses a novel scheme to manage transitions between the active and passive control modes. In particular, the controller applies an explicit
smoothing method to address discontinuities in the command torque at phase transitions. The implementation proposed uses an exponential weighting function of the form where $\tau_{\text{inv}}$ is the inverse dynamics torque associated with the robot model, $f_{\text{weighting}}$ is the weighting function, $a$ is a sensitivity factor, and $N$ describes the duration of the transition period. The transition duration period as well as sensitivity factor appear to be hand tuned parameters.

In addition to phase transition smoothing, a pre-transition control method is applied at the end of the stance phase prior to the passive swing phase in order to affect smooth phase transitioning. The pre-transition control works by measuring the ground reaction force and setting a minimum threshold value. When the GRF drops below the threshold the system enters a passive swing control mode, i.e., the bypass valve at the actuators are opened. The objective of this method is to reduce the phase transition delay due to residual pressure in the foot sensors.

### 7.4 Assessment and Recommendations

The mechanical as well as control design of the Hydraulic Lower Extremity Exoskeleton was straight-forward and contained many aspects which we support. In particular, we supported the use of off-the-shelf components in the hardware design and the addition of bypass valves to take advantage of passive dynamics during walking to produce more energy conscious behaviors.

The control system for this hardware effectively created a “get out of the way design” using the torque sensed at the joints only. In the short-term, this type of policy seems to be a good strategy. The other highlight of the outlined control policy was the smoothing function which was used during phase transitions in the walking gait cycle. A similar type of smoothing will most likely be beneficial in terms of operator experience for a variety of different operational modes in which different phase transitions occur, e.g., running, jumping, etc.
One potential drawback of this hardware is the power system. The documentation in [1] was sparse with respect to the exact specifications of the motor and energy storage device which powers the hydraulic system. Additionally, in the long-term control design strategy, pure get out of the way control using measurements of the suit only has drawbacks, as mentioned previously. This strategy will ultimately lead to a “sensitivity amplification” - like behavior. This strategy will thus be positively sensitive to user intended motion and negatively sensitive to external disturbances.

The figures as well as hardware and control specifications in this section are taken from [1].

References


8 IHMC Mobility Assist Exoskeleton (MAE)

Although the IHMC MAE was primarily designed as a disabled assist exoskeleton, the device also provides a “performance enhancement” control mode, which is within the scope of this document. The main design principle highlighted in the IHMC MAE hardware (a recurring theme throughout the exoskeleton literature) is that directly measuring user intent can be difficult for a number of reasons. The IHMC designers resolve the issue using a new control and feedback system, which for the IHMC MAE, is primarily based on a unique actuation scheme.

The IHMC MAE uses novel series elastic actuators (SEAs) in their hardware design mostly because they offer the ability to perform high-fidelity impedance control. In series elastic actuators, a compliant element is placed in series after the output a motor’s drive mechanism. The measured compression of the compliant element is used to calculate the force, or torque, acting on the output of the actuator. **Series elastic actuators** are generally viewed as a good way to provide **accurate force feedback** information and to provide a **low mechanical impedance**. The major disadvantage of SEAs is that they have a relatively low bandwidth at high forces, as the compliant element needs time to compress before a force can be sensed and thus inherently include a delay between the time a force is applied and when the control system can react.

8.1 Actuator specifications

The IHMC actuators are designed based on data collected from clinical gait analysis. Specifically, the actuators at the hip and knee were designed to be able to provide 40Nm of peak torque during the stance phase of the walking gait cycle. The rotary SEA is composed of a Moog BN34-25EU-02 brushless DC motor with a 1:100 harmonic drive (SHD-20).

The spring mechanism, which sits between the gearbox and joint output, is shown in Figure 8. The mechanism uses linear die springs and an angular encoder to measure the
joint torque output. The choice of linear die spring was based on the spring’s predictable force to displacement function as well as favorable energy storage to weight characteristics.

![Schematic of the SEA elastic mechanism design](image)

Figure 8: Schematic of the SEA elastic mechanism design, shown in the zero force position. The encoder reads a scale tape on the curved cylindrical surface. Note that the actuator housing and bearing have been omitted for clarity.

Fully assembled, the actuator has a **torque limit of 80 Nm**, with a **velocity limit of 6.8 rad/s**. As noted, the **bandwidth of the actuator** is its primary drawback, which limits the torque control to approximately **10 Hz at amplitudes greater than 15 Nm** and up to **30Hz for lower magnitude forces**.

### 8.2 Exoskeleton Specifications

The IHMC MAE lower extremity exoskeleton includes a total of ten degrees of freedom (DOF), six of which are active and four are passive. Five DOF correspond to the two legs of the system. Each of the powered joints is powered using the SEA joint discussed in the previous subsection. A labeled diagram of the IMHC system is shown in Figure 9.

The hip adduction/abduction as well as flexion/extension DOFs are actively actuated. The hip yaw DOF consists of a curved spring-loaded roller bearing whose center of rotation is approximately at the user’s hip joint. The knee flexion/extension joint is connected to the hip flexion/extension joint using telescoping tubes and is also actuated. The final DOF is the dorsal flexion at the ankle joint. This joint is spring loaded such that it provides unidirectional torque for toe clearance during walking.

In its current configuration, the IHMC exoskeleton is controlled by an off-board computer and is powered using a tether. The suit includes position and force sensors in the actuators in addition to two foot switches per foot. The foot switches are used to detect whether the system is in single or double support phase. It also provides information used to estimate the load distribution to the stance legs.

### 8.3 Control Specifications

Both IHMC MAE control approaches noted are relatively straightforward implementations of low-level torque control. The first control scheme takes full advantage of the SEA actuators’ ability to directly measure output torque and subsequently to perform closed-loop
The controller takes in a desired torque, compares the desired value to the output torque measured at each individual actuator, then uses this value as well as its derivative to compute an actuator command signal, which in this case is a current. The largest question in this controller, as presented in literature, is how to define the desired torque term $\tau_{\text{des}}$.

The second low-level control approach presented in the IHMC MAE literature is a combination of a position-based controller with an inner-loop torque controller. This control scheme is presented in Figure 11. The controller in Figure 11 shows an outer-loop position-based PD controller that takes in desired joint trajectories and compares them to measured joint positions. These are used to generate desired torque values which are fed into an inner closed-loop torque control loop. This control scheme is a good low-level choice if high-impedance, accurate suit motion is desired. Similarly to the torque-only control loop above, the main question in this control scheme is how to obtain the desired joint trajectories.

One possibility for defining either the desired torques / joint trajectories in these control schemes is to use clinical gait analysis data. With this approach, the highlighted controllers would effectively play back nominal joint trajectory data. The foot sensors in the system
would detect phase transitions, allowing the controllers to dynamically adjust the prerecorded data to the user in realtime.

8.4 Assessment and Recommendations

The design of the IHMC MAE is in many ways centered around being able to perform high-fidelity force control. In general we support the ability to perform force control using a direct measurement (or near direct) of the force/torque at the output of the transmission system. Series-elastic actuators may provide a solution to this problem for a number of operational scenarios, but caution should be taken when considering this solution for highly dynamic behaviors, as the control bandwidth at the actuator may be too slow to safely react in dynamically changing environments.

One potential other issue with the IHMC control design is that they only appear to address low-level control. The designers have not specified how to generalize the process of generating torque/joint reference trajectories, in other words there is a lack of information with respect to the typical “mid-level” of a hierarchical control scheme. Thus combining other approaches with the low-level, highly accuracy torque control provided by the novel SEAs presented in this section could offer a potentially beneficial control solution.

All of the figures as well as hardware and control specifications in this section are taken from [1].

References


9 MIT Exoskeleton

The MIT Exoskeleton is based on evidence from biology and passive walking devices that suggest that legged locomotion can be very efficient. The main physical concept behind this efficiency being that there is a gait cycle for a pair of legs that naturally exchanges energy between gravity and inertia. The main mechanical design principles center around the use of a combination of passive and active elements. In particular, the MIT design uses springs, variable impedance joints, and powered actuators. The suit generally functions as a lightweight, underactuated robot that runs in parallel to an operator and supports the
weight of a payload. Additionally, the leg structure of the suit allows weight from the suit and payload to be transferred directly to the ground.

Of the several other design principles discussed, the MIT team emphasizes that joint powers scale linearly with mass. Also, the team points out that alterations in the operator’s gait pattern have been shown to increase the physiological energy expended during locomotion. Thus, the specifications for actuation and control for their system are extracted from the angle, torque, and power data of human walking joint patterns.

9.1 Actuator specifications

The MIT exoskeleton uses a single actuator located at the hip. The actuator is designed around a total system weight of 165 kg. The maximum scaled hip torque for a system with this mass is approximately $-130\,\text{Nm}$ during the stance phase and approximately $100\,\text{Nm}$ during the swing phase of the gait. The hip is chosen as the actuated joint because proximal mass is metabolically less expensive in walking than distal mass.

The specific choice of actuation for the MIT exoskeleton hip joint was a linear series elastic actuator. This choice provided a lightweight and relatively inexpensive means of implementing force control with a bandwidth similar to that of natural muscle. A model of the actuator is shown in Figure 12. Like all series elastic designs, the actuator shown in Figure 12 includes a spring in series with the output of the motor drive system of the actuator. The motor-drive mechanism consists of a brushed DC motor driving a 3mm ball screw via a 2:1 reduction belt drive. The nut of the ball screw is coupled to the actuator output shaft via four compression die springs. The compression of the die springs are measured using a linear potentiometer, which is how forces at the output are measured. The team selected a 150W Maxon RE40 Brushed DC motor for the actuator based on the bio-mechanical data and its power and weight ratio. The force bandwidth for this actuator was characterized during both stance and swing phases of the walking gait cycle. During stance, the bandwidth of the actuator was 35 Hz, while the bandwidth during swing was found to be 40Hz.

Figure 12: Linear series elastic actuator.
9.2 Exoskeleton Specifications

The MIT exoskeleton design has a total of fourteen degrees of freedom, three at each hip, one at each knee, two at each ankle, and one in each foot. A cam mechanism implemented at the hip joint enables hip ab/adduction. This system was necessary because, during abduction, there is a length difference between the operator and exoskeleton leg which results from having non-collocated centers of rotation. The cam mechanism automatically adjusts the exoskeleton leg length such that the center of rotation of the exoskeleton hip is projected onto the biological hip center of rotation. A picture of the MIT exoskeleton is shown in Figure 13.

The interface between the suit and operator consists of shoulder straps, a compliant waist belt, thigh cuffs, and a shoe connection. The MIT exoskeleton employs a custom-built sensor that measures the interaction force between the exoskeleton and the operator’s thigh. The sensor consisted of a spring pack, where the deflection of the passive springs was measured with a spring-loaded linear potentiometer.

The exoskeleton implements a **variable damper knee mechanism** in the flexion/extension degree of freedom using a magnetorheological damper. The damper can exert a **maximum braking torque of 60 Nm** and consumes on average **1W of electrical power**. Additionally, a linear spring at the ankles captures negative energy during dorsiflexion. The energy stored is released during plantar flexion to add energy to the system as the foot comes off the ground. A urethane spring (247 kN/m) is used as a liner spring in a lever compression assembly. With a lever arm of 0.0381 m, the assembly yields a spring rotary stiffness of 356 Nm/rad.

A unidirectional spring assembly is also used in the hip ab/adduction degree of freedom. The spring allows the hip to freely abduct. The effective rotary stiffness of the spring assembly is 96 Nm/rad in order to provide the 8 Nm required during adduction.

The suit uses a 48V battery pack and is instrumented with **rotary potentiometers** at the hip and knee. Additionally, **strain gages** were placed on the structure of the exoskeleton shank to measured sagittal bending moment and compression force.

![Figure 13: Sensors placed on the exoskeleton leg](image)
9.3 Control Specifications

The MIT exoskeleton controllers use the fact that desired actuation and active damping at the knee are functions of gait cycle. Hence, the values of these desired functions can be determined from human walking data. Fundamentally, the control strategy works as a state machine that uses joint angle and measured forces to implement state transitions.

Figure 14: Summary of the actuation control of the exoskeleton leg as a function of gait cycle with an actuator at the hip and a damper at the knee. The ankle is completely passive but is included for completeness.

The walking cycle around which the MIT control scheme was designed is shown in Figure 14. The individual control strategies in the various phases of the walking cycle are highlighted in Figure 14. For the hip there are four distinct strategies. During the thrust phase, the hip exerts a torque that helps to raise the center of mass of the system. During the extension spring phase, a virtual spring stiffness allows energy to be virtually stored while the center of mass moves forward. During the swing assist phase the virtual energy is released, resulting in a torque being applied which assists in swinging the leg forward. Finally, in leg retraction a torque is applied to help with foot placement and weight acceptance. A diagram that illustrates how the sensors in the shank and hip joint are used to switch between these various phases is show in Figure 15.

Figure 15: State-machine diagram for the hip controller.

The knee controller in the MIT exoskeleton effectively functions independently from
the hip controller. During knee strike, the variable damper in the knee exerts a torque proportional to the rotational velocity of the knee joint. A residual magnetic field remains in the knee joint after it is turned off, creating a resistive torque. The knee therefore needs to be actively demagnetized at full extension during the last phase of stance to allow it to swing freely during the subsequent swing phase. The state machine diagram that illustrates how the various phase transitions for the knee joint were implemented using the exoskeleton’s on-board sensors is in Figure 16.

![Figure 16: State-machine diagram for the knee controller.](image)

### 9.4 Assessment and Recommendations

The MIT hardware and control system present a well designed system that focuses primarily on efficiency in design. We generally support the series-elastic linear ball screw hardware design for their mechanical efficiency as well as ability to perform high fidelity force control. Although, these drives will again be limited by bandwidth issues in highly-dynamic maneuvers. The use of a strain gage in the shank was also a novel means of measuring ground reaction forces. This design may offer benefits in terms of repeatability over different operators, as foot fall patterns may include significant variations for different users or even in the same user in different environments.

The details on the controllers were somewhat sparse in the sense that, at least in [1], the exact means through which the added torques discussed above were derived was not provided. Overall, we support the design of the controllers in the sense that they explicitly took the biomechanics of walking into account in their design and implementation. A similar approach for a variety of different behaviors may be very beneficial.

The hardware specifications and associated figures in this section were taken from [2]. The discussion on control design and and the associated figures therein are respectively based on and taken from [1].

### References

10 RoboKnee

The RoboKnee is a prototype system designed to enhance human strength, endurance and speed. To achieve these goals, RoboKnee uses a low-impedance mechanical system that incorporates a natural user interface, long life, and is comfortable to wear. The suit’s controller implements a “get out of the way” control scheme, where the system interacts with the user through a low-impedance interface. This section focuses on RoboKnee’s linear series elastic actuator design and the novel control method the device employs to coordinate its single powered knee joint.

10.1 Actuator specifications

The RoboKnee actuator is specifically designed to provide low impedance and high force feedback fidelity. The device uses a series elastic actuator to obtain robust output force measurements. The series elastic actuation scheme allows RoboKnee to avoid load cells, which are both delicate and expensive.

The actuator used in the RoboKnee device (see Figure 17) consists of a drive train and output carriage. These two sub-assemblies are coupled through die compression springs. A servo motor directly connected to a ball screw assembly drives a ball nut flange that pushes on a spring retaining plate. A secondary spring retaining plate is coupled to an output assembly. By measuring the deflection in the die springs, RoboKnee is able to obtain the force applied to the output of the linear SEA.

Figure 17: Exploded view of a series-elastic actuator.

The linear actuator pictured in Figure 17 weighs 1.13 kg, has a stroke length of 30.5 cm and diameter of 5.8 cm. The maximum speed of the actuator is 28 cm/s. The actuator’s maximum continuous force is 565N and its maximum peak force is
1,330 N, with a maximum continuous power of output of 164 W, and maximum peak power of 634 W.

The force control bandwidth of the RoboKnee actuator is dependent on the magnitude of the force. Larger forces can induce significant time delays due to the time it takes for the spring to compress. Thus, the small force control bandwidth of the system is 35 Hz and the high force bandwidth is around 7.5 Hz.

10.2 Exoskeleton Specifications

The RoboKnee mechanism consists of a single actuated degree of freedom powering the flexion/extension of the operator’s knee joint. Note that the mechanism itself does not provide a pathway for transferring weight from a load directly to the ground. The mechanism transfers loads directly to the users musculoskeletal structure, and focuses primarily on augmenting user knee joint torques.

The RoboKnee device is composed of an off-the-shelf knee brace modified with structural pieces to extend the brace and provide actuator attachment points (see Figure 18). The exact length between actuator attachment points is not listed in the literature, but it appears that the attachment points are at minimum the stroke displacement (30.5cm) of the actuator away from each other.

RoboKnee uses a linear potentiometer spanning the spring retaining plates to measure displacement in the springs and subsequently to measure force at the actuator output. The forces between the users foot and the ground are also measured using single axis load cells. Potentiometers which measure the knee joint angle are also employed in this design.

The single actuator as well as control and sensor electronics are run using 4 kg of nickel-metal-hydride batteries, which give the system only about 30-60 minutes of heavy use.
10.3 Control Specifications

RoboKnee employs a hierarchical control strategy, which uses a straightforward mid-level force generation scheme coupled with a low-level closed-loop force-based control loop. The low-level (joint level) control is a PD control loop.

The RoboKnee’s mid-level controller uses several simplifying assumptions to perform “force amplification” to offload a percentage of the torque required by the user to actuate the system’s knee joint. This is achieved through positive force feedback amplification. The approach uses the measured ground reaction force to calculate the torque that would be required to produce this force in a static situation,

$$\tau = \mathbf{R} \times \mathbf{F}.$$ 

The \( \mathbf{R} \) term represents the vector from the ground reaction force to the user’s knee and \( \mathbf{F} \) is the ground reaction force. Note that in RoboKnee’s implementation, \( \mathbf{F} \) can only be estimated due to the fact that the ankle joint angle and the ground reaction force is assumed to be purely vertical (a limitation induced by the single axis force sensors on the user’s feet).

Once the estimated joint torque, \( \tau \), is calculated, an amplification factor specifies how much of the required knee torque will be provided by the control system. For example, with unity amplification factor, the actuator would completely compensate for the sensed ground reaction forces. Similarly, with zero amplification, the exoskeleton provides no force.

10.4 Assessment and Recommendations

The RoboKnee is a single-joint system that highlights several hardware and control design concepts that we generally support. We again support the use of a linear ball screw with a series elastic element to enable high mechanical efficiency and high-fidelity force control in low to medium speed maneuvers. The concept of using measured ground reaction forces to directly produce desired knee joint torque is interesting in the sense that it is simple and relies on minimal information.

The largest potential issues with the RoboKnee are that the forces of the mechanism and any load carried by the operator are fully transferred through the user’s musculoskeletal structure. Additionally, the large moment arm of the actuator significantly increases the effective volume of the operator-system leg, and as such may reduce overall mobility in densely-packed areas.

The discussion as well as figures in this section are respectively based on and taken from [1].

References

11 Conclusions and Recommendations

The (strength augmentation) exoskeletons we reviewed can be categorized into two general control categories. The exoskeleton either directly measures user intent (e.g., from EMG data or direct human-exoskeleton interaction forces), or it estimates intent from measurements at the exoskeleton joints and applies a sensitivity amplification strategy to shadow the wearer.

Directly measuring user intent is difficult to implement using standard sensing modalities. For instance, EMG data is notoriously noisy and presents both modeling and calibration challenges. It would also be extremely difficult to keep these sensors in place to obtain accurate readings in dynamic environments or activities. For similar reasons, many systems avoid the use of load cells or complicated sensor networks to accurately obtain operator-robot interaction forces/torques.

Sensitivity amplification strategies circumvent many of the direct operator-robot sensing issues by estimating human intent from measurements of the exoskeleton hardware. The issue with this policy is that it cannot generally distinguish between user generated torques and those produced by external sources. As such, they end up amplifying not only the user’s intent, but also external disturbances, requiring the operator to expend valuable energy to stabilize the system. In dynamic situations the operator may not be capable of actively stabilizing the exoskeleton.

Based on these observations, we recommend (at least in the short term) fusing the two predominant approaches to exoskeleton control. That is, combining sensitivity amplification strategies with direct user measurement to robustly distinguish user intent from external disturbances. For instance, it may be possible to use low information density EMG (thresholded on/off muscle activation signals) with robot force/torque and angular measurements to filter disturbances from operator-robot interaction forces. As a longer term solution, we highlight research in the area of MEMs, nano-fabrication, soft sensors, etc., which has lead to the development of new, flexible “robotic skin” sensing arrays. Integrating these sensing arrays into operator clothing (or attaching directly to the exoskeleton), it may be possible to directly measure human interaction forces (i.e., estimating pressure / force and exoskeleton contact locations), which was not feasible in the recent past. Dense sensing arrays add redundancy and can improve measurement reliability and, thereby, feedback control performance.

We also highly stress the importance of high-bandwidth control loops. It is important that an exoskeleton’s control bandwidth stays well above (typically 2 – 3×) the human control bandwidth (2 – 5 Hz), to track dynamic motion. Several of the reviewed exoskeletons controllers are close to lower limit of this human bandwidth threshold under no-load conditions, and so can interfere in dynamic tasks. Note that these bandwidth issues are primarily a function of the exoskeleton hardware, and thus special care/analysis needs to be given/conducted to make sure that the hardware is capable of physically producing required behaviors.

Lastly, the importance of producing hardware that is physically capable of achieving dynamic performance is fundamentally linked to how mass is distributed throughout the system. In general, it is desirable to minimize mass, particularly in distal regions. The design objective is often achieved by focusing actuation and leaving certain degrees of freedom passive (leading to an underactuated system). Underactuated control is a complicated problem that is often ignored in the sense that controllers assume the operator will provide
necessary forces and torques for the un-actuated degrees of freedom. Though it is possible to deal with the underactuated control problem directly (e.g., optimization-based controllers), there is a balance between feedback and feedforward control. By developing better sensors and feedback controllers that directly measure and shadow operator intent, exoskeleton controllers will become more robust and less sensitive to errors due to underactuated system assumptions and dynamic model inaccuracies.
12 Appendix: Other exoskeleton systems

The web links (URLs) below can be clicked on to view, if your PDF viewer/browser supports that. On our browsers you actually have to click on the black part of a letter, not just in the blue box (if present).

12.1 Overviews

http://powerexoskeletons.com/
http://exoskeletonreport.com/
http://robohub.org/tag/exoskeleton/
http://robohub.org/exoskeletons-new-and-older/
http://neurogadget.com/tag/exoskeleton
http://www.engadget.com/tag/exoskeleton/
http://spectrum.ieee.org/robotics/medical-robots/exoskeletons-around-the-world
http://spectrum.ieee.org/biomedical/bionics/the-rise-of-the-body-bots
http://www.extremetech.com/electronics/139633-will-we-ever-have-iron-man-exoskeletons
https://prezi.com/jygcvfxiesmm/a-brief-introduction-to-biomechanical-exoskeletons/
http://nextbigfuture.com/2015/03/lower-body-exoskeleton-audi-chairless.html

We do not have sufficient information to survey the following exoskeletons.

12.2 Commercial exoskeletons for augmentation

12.2.1 Sarcos XOS/WEAR

We do not have sufficient non-proprietary information to survey this system.


12.2.2 Lockheed Martin HULC, FORTIS

We believe this is in collaboration with Ekso Bionics and is similar to BLEEX.

http://www.dailytech.com/From+HULC+to+FORTIS+the+Evolution+of+Lockheed+Martins+Incredible+Exosuit/article36421.htm
http://www.wired.com/2014/09/navys-exoskeleton-could-make-workers-20-times-more-
12.2.3 Revision Military

PROWLER Human Augmentation System (HAS) Exoskeleton.
https://www.youtube.com/watch?v=RKcqHaPhkM
https://www.youtube.com/watch?v=Zq4amM9u-6o

12.2.4 Activelink/Panasonic

A variety of exoskeleton products.
http://activelink.co.jp/en

Assist Suit AWN-03:
consists of a 13-pound backpack outfitted with leg supports which allows its wearer to lift up to 33 pounds without any noticeable effort.
http://www.engadget.com/2015/08/20/japans-top-oil-company-is-building-an-aliens-power-loader/

Power Loader Suit:

12.2.5 DAEWOO


12.2.6 Innophys: Muscle Suit

Appears to be a power assist suit for lifting. Sip and puff interface? Tokyo University of Science Prof. Hiroshi Kobayash.
https://innophys.jp/
video: https://www.youtube.com/watch?v=Sqr1l909WPw
video: https://www.youtube.com/watch?v=mNdJgh0ZcrM
video: https://www.youtube.com/watch?v=NtX81pf-3G4
12.2.7 Noonee (Swiss)

Chair exoskeleton. Passive?

[Link to article](http://www.extremetech.com/extreme/188417-rejoice-commuters-and-workers-the-chairless-chair-exoskeleton-lets-you-sit-down-anywhere-anytime)

12.2.8 Sagawa Electronics (Swiss)

Increases reach. Master exoskeleton inside larger slave exoskeleton. Running demonstrated.

[YouTube video](https://www.youtube.com/watch?v=tYgHdxeMCCAI)

[Link to article](http://www.ohgizmo.com/2013/07/11/mk3-exoskeleton-suit-promises-to-make-schoolgirls-better-taller-stronger/)

[Link to article](http://www.bitrebels.com/technology/powered-jacket-exoskeleton-japan/)

12.2.9 RB-3D

Hercule

[Link to website](http://www.rb3d.com/produits/exosquelettes/)

12.3 Academic exoskeletons for augmentation

12.3.1 Kanagawa Institute of Technology

Pneumatic exoskeleton developed at the Kanagawa Institute of Technology, in Atsugi, Japan, allows Akiko Michihisa, a fitness trainer, ...

[Link to article](http://www.ubergizmo.com/2007/10/air-pressure-exoskeleton/)

12.3.2 Monash University/Chen

[Link to article](http://www.dailymail.co.uk/sciencetech/article-2639939/Super-fireman-The-hi-tech-exoskeleton-firefighters-superhuman-abilities.html)

[News article](http://news.discovery.com/tech/robotics/firefighter-exoskeleton-to-the-rescue-140521.htm)
12.4 Commercial exoskeletons for assistance and rehabilitation

12.4.1 ReWalk

On the sixth generation of this device.
http://rewalk.com/

12.4.2 Cyberdyne

up to HAL 5 (already covered)
http://spectrum.ieee.org/robotics/medical-robots/exoskeletons-are-on-the-march
http://www.computerweekly.com/photostory/2240108388/Photos-Cyberdyne-Hal-robotic-
exoskeleton-to-help-paralyzed/7/Japan-beats-the-US-to-it-Cyberdyne-Hal-robotic-
exoskeleton-to-help-paralyzed
http://www.dailymail.co.uk/sciencetech/article-2384930/Robotic-exoskeleton-help-
rehabilitate-disabled-people-passes-safety-tests--paving-way-sale-UK.html

12.4.3 Rexbionics

REX exoskeleton
http://www.rexbionics.com/
http://www.gizmag.com/rex-robotic-exoskeleton/15736/pictures
http://www.stripes.com/news/exoskeleton-could-benefit-troops-with-spinal-cord-
injuries-1.113657
http://www.funis2cool.com/cool/rex-the-robotic-exoskeleton-could-change-the-
lives-of-disabled-people.html

12.4.4 Indego/Parker Hannafin

Commercialization of Vanderbilt exoskeleton
https://www.youtube.com/watch?v=-bYYmZNxaZk
http://www.robotictrends.com/article/parker_hannifin_indego_exoskeleton
http://www.crainscleveland.com/article/20141112/BLOGS03/141119915/parker-hannifin-
accepts-the-challenge-of-commercializing-the-indego--41951672-812546791-1442419256=:
6352--:

12.4.5 Honda

2 devices in the Walking Assist Program: Bodyweight Support Assist and Stride Management Assist (SMA):
http://corporate.honda.com/innovation/walk-assist/
http://world.honda.com/Walking-Assist/
12.4.6 Hyundai

Appears to be similar to BLEEX.
Hyundai’s exo project is lead by Dongjin Hyun who did his PhD with Homayoon Kazerooni at UC Berkeley and a PostDoc with Sangbae Kim at MIT.

12.4.7 3D Systems

3D printed exoskeleton. Using Ekso Bionics technology.
http://www.dezeen.com/2014/03/05/3d-printed-exoskeleton-helps-paralysed-users-walk/

12.4.8 ExoAtlet (Russian)

Appears to be similar to BLEEX.
http://robohub.org/clinical-trials-begin-for-russias-first-medical-exoskeleton/

12.5 Academic exoskeletons for assistance and rehabilitation

12.5.1 Vanderbilt

Commercialized by Indego/Parker Hannafin
https://en.wikipedia.org/wiki/Vanderbilt_exoskeleton
http://research.vuse.vanderbilt.edu/cim/research_orthosis.html

12.5.2 Mindwalker

Key feature is actuation in lateral plane. Each of the powered joints has a series elastic actuator, which can deliver 100 Nm torque and 1 kW power.
https://mindwalker-project.eu/
http://www.3me.tudelft.nl/en/about-the-faculty/departments/biomechanical-engineering/research/dbl-delft-biorobotics-lab/exoskeleton/
http://www.utwente.nl/ctw/bw/research/projects/MINDWALKER/
12.5.3 U. Penn

Student project that got some press.


12.5.4 East China University of Science and Technology

Fully portable hydraulic exoskeleton. Unclear if this is for assistance or augmentation.

Video: http://v.youku.com/v_show/id_XMTg3MTQzNjgw.html

Heng Cao: “most difficult thing was control bandwidth”, so they are probably not using high quality valves.

http://mech.ecust.edu.cn/s/131/t/147/6a/07/info27143.htm

12.5.5 University of Electronic Science and Technology of China

Prof Hong Cheng did his Postdoc in CMU from 2006-2009 in CS. He is very famous in China for his exoskeleton work.


http://uestcrobot.net/~hcheng/

http://www.uestcrobot.net/?q=node/291

12.6 Government Programs

12.6.1 TALOS

We assume the reader is familiar with this program.

12.6.2 DARPA Warrior Web

We assume the reader is familiar with this program.

12.6.3 Japan: NEDO

There was a Japanese government (NEDO) oriented project, “Robotic Devices for Nursing Care Project”, that intended to boost the practical nursing care robots development, including exoskeleton.

http://robotcare.jp/?lang=en

http://robotcare.jp/?page_id=29&lang=en

They made a center to test the safety for robots including exoskeletons.

http://www.rtnet-biz.jp/rtsic/
12.6.4 EU: BALANCE program

http://balance-fp7.eu/
http://cordis.europa.eu/project/rcn/106854_en.html