2005 IEEE/RSJ International Conference on Intelligent Robots and Systems

On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX)

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Abstract - **The first energetically autonomous lower extremity exoskeleton capable of carrying a payload has been demonstrated at U.C. Berkeley. This paper summarizes the mechanical design of the Berkeley Lower Extremity Exoskeleton (BLEEX). The anthropomorphically-based BLEEX has seven degrees of freedom per leg, four of which are powered by linear hydraulic actuators. The selection of the degrees of freedom and their ranges of motion are described. Additionally, the significant design aspects of the major BLEEX components are covered.**

Index Terms – BLEEX, exoskeleton, wearable robotics, mechanical design, legged locomotion

I. INTRODUCTION

Heavy objects are typically transported using wheeled vehicles. However, many environments, such as rocky terrains and staircases, pose significant challenges to wheeled vehicles. Thus legged locomotion becomes an attractive method of transportation within these settings, since legs can adapt to a wide range of extreme terrains. The Berkeley Lower Extremity Exoskeleton (commonly referred to as BLEEX) is the first field-operational robotic system which is worn by its operator and provides its wearer the ability to carry significant loads on his/her back with minimal effort over any type of terrain.

BLEEX is comprised of two powered anthropomorphic legs, a power supply, and a backpack-like frame on which a variety of heavy payloads can be mounted (Fig. 1). BLEEX provides load carrying capability through legged locomotion guided by human interaction, but instead of actively “driving” the vehicle, BLEEX shadows the operator’s movement as he/she “wears” it like a pair of artificial legs. By combining the strength capabilities of robotics with the navigation intelligence and adaptability of humans, BLEEX allows heavy loads to be carried over rough, unstructured, and uncertain terrains.

Exoskeletons are usually conceived as systems including upper extremities, lower extremities, or both; the BLEEX project focuses solely on lower extremity exoskeletons. Upper extremity exoskeletons are generally for manipulating heavy objects and are usually used in warehouses, manufacturing facilities, and distribution centers (e.g. [1] – [4]). Lower extremity exoskeletons are generally for carrying heavy objects long distances (usually outdoors) and on paths that are not passable by wheeled vehicles. There is no practical reason for using a lower extremity exoskeleton in a setting where wheeled vehicles can be used or where distances are so short that overhead cranes are practical. Lower extremity exoskeletons are most suited for carrying heavy objects along unstructured, outdoor paths.

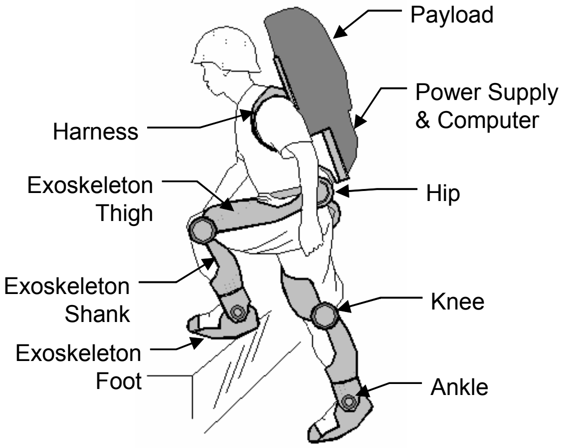

Fig. 1 Conceptual sketch of a lower extremity exoskeleton. Proper actuation of the robotic legs removes the payload weight from the wearer, while allowing the wearer to effortlessly control and balance the machine.

BLEEX has numerous applications; it can provide soldiers, disaster relief workers, wildfire fighters, and other emergency personnel the ability to carry major loads, such as food, rescue equipment, first-aid supplies, communications gear, and weaponry, without the strain typically associated with demanding labor. It is our vision that BLEEX will provide a versatile transport platform for mission-critical equipment.

II. BACKGROUND

The first active exoskeletons appeared in the late 1960’s and early 70’s at General Electric (GE) and the Mihajlo Pupin Institute in Belgrade. The Hardiman project at GE [5] was a large, full-body exoskeleton weighing 680 kg and controlled using a master-slave system. Safety concerns and complexity issues prevented it from ever walking, or even stably moving the legs.

The Belgrade exoskeleton was a human-sized lower extremity robot designed to help rehabilitate paraplegics [6]. Similar to the Hardiman project, it could never carry its own power source. The Belgrade exoskeleton only followed pre-programmed walking motions, which greatly limited its usefulness. However, this project did produce Zero Moment Point control, which is still used in humanoid robots.

This work is partially funded by DARPA grant DAAD19-01-1-0509.

Following the 1970 attempts, relatively few people investigated lower extremity exoskeletons. One project in 1993 was the Electric Power Extender at the University of California at Berkeley [1]. This full-body exoskeleton used electric actuation to amplify human capabilities similar to the Hardiman. The Berkeley project used force sensors to detect and amplify the human's forces, but still had limited success in walking.

The 21st century has seen resurgence in exoskeleton investigation. In Japan, the Kanagawa Institute of Technology has developed a full body "wearable power suit", powered by unique pneumatic actuators [7]. The forces at their three actuators (knee, waist, and elbow) are controlled by measuring the hardness of the corresponding human muscles. Limited actuation and lack of a portable power supply restricts this exoskeleton's applications.

Tsukuba University in Japan developed the lightweight power assist device, HAL [8]. Using EMG sensors on the human's leg muscles and ground reaction force sensors, HAL controls its electric actuators at the knee and hip. This exoskeleton has a portable power supply, but only assists the operator's leg muscles; it cannot carry an external load.

Still in development are several other lower extremity exoskeletons designed to aid disabled persons ([9] – [11]). Besides exoskeletons, some other active lower extremity devices are worth mentioning. A modern rehabilitation device is the lower limb locomotion trainer, Lokomat ([12] and [13]). Instead of carrying a load, the robot's torso is mounted to a stand and moves the operator's feet in a predetermined path. While not an exoskeleton, the Lokomat is a successful product that faces similar challenges. The RoboKnee, developed by Yobotics, is a powered knee orthotic designed to enhance the operator's strength and endurance during walking [14]. RoboKnee uses ground reaction forces to estimate the desired knee torques. Alternatively, researchers at Hokkaido University in Japan are creating a power assist device for the lower back [15]. Attached at the thigh and torso, the device uses EMG sensors to control its electric motors. A variety of other active orthoses are also being developed, such as a pneumatic muscle powered ankle orthotic [16].

The Berkeley Lower Extremity Exoskeleton (BLEEX) project has developed an energetically autonomous exoskeleton capable of carrying its own weight plus an external payload. All previous exoskeletons are either tethered to a fixed power supply or not strong enough to carry an external load. Also, BLEEX transfers the payload forces to the ground instead of wearer, unlike orthoses and braces. To combat the complexities inherent with creating a walking exoskeleton, the BLEEX project developed a novel control scheme, which eliminates measurements of the human or human interaction with the robot.

III. EXOSKELETON CONTROL

The BLEEX control algorithm ensures that the exoskeleton shadows the operator with minimal interaction forces between the two. Additionally, the control scheme needs no direct measurements from the operator or where the operator contacts the exoskeleton (e.g. no force sensors between the two); instead, the controller estimates, based on measurements from the exoskeleton only, how to move such that the pilot feels very little force [17]. The control method eliminates the problems associated with measuring interaction forces or human muscle activity.

The basic principle for the control of BLEEX rests on the notion that the exoskeleton needs to shadow the wearer's voluntary and involuntary movements quickly, and without delay. This requires a high level of sensitivity in response to all forces and torques the pilot imposes on the exoskeleton. The BLEEX control increases the closed loop system sensitivity to the operator's forces and torques by measuring variables only from BLEEX [17].

The BLEEX control scheme does have two realistic concerns. First, an exoskeleton with high sensitivity to external forces responds to external forces whether or not they are from the operator. For example, if someone pushed against an exoskeleton that had high sensitivity, it would move as if the forces were from its operator. The key to stabilizing the exoskeleton and preventing it from falling in response to external forces depends on the operator's ability to move quickly (e.g. step back or sideways) to create a stable situation for herself/himself and the exoskeleton. For this, a very wide control bandwidth is needed so the exoskeleton can respond to both the operator's voluntary and involuntary movements (i.e. reflexes). The second concern is that this control method has little robustness to parameter variations and therefore requires a relatively good dynamic model of the system [17].

IV. DESIGN ARCHITECTURE

Fundamental to designing a lower extremity exoskeleton is selecting the overall structural architecture of the legs. Many different layouts of joints and limbs can combine to form a functioning leg, but any architecture generally falls into one of a few categories:

A. Anthropomorphic Architecture

Anthropomorphic architectures attempt to exactly match the human leg (Fig. 2). By kinematically matching the human degrees of freedom and limb lengths, the exoskeleton's leg position exactly follows the human leg's position. This greatly simplifies many design issues. For example, one does not have to be concerned with human/exoskeleton collisions. However, one major difficulty is that the joints in human legs cannot be duplicated using the common state of technology in designing joints. For instance, the human knee does not exhibit a pure rotation and duplicating all its kinematics will result in a complicated (and perhaps non-robust) mechanical system. Another major point of concern in this architecture is that the exoskeleton limb lengths must be equal to the human limb lengths. This means that for different operators to wear the exoskeleton, almost all the exoskeleton limbs must be highly adjustable. In general, the anthropomorphic architecture is erroneously regarded to be the preferred choice because it allows the exoskeleton to attach to the operator wherever desired.

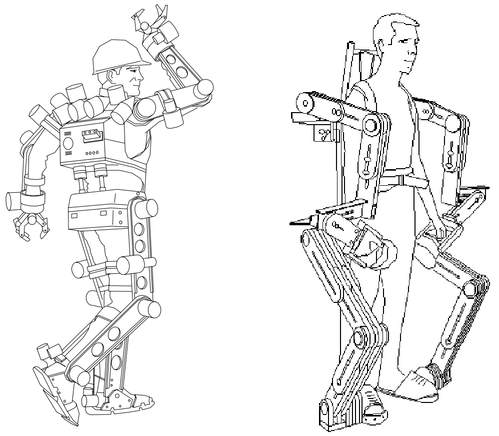

Fig. 2 Examples of Anthropomorphic Architecture (Left) and Non-Anthropomorphic Architecture (Right)

B. *Non-anthropomorphic Architecture*

While not as common in exoskeleton designs, many non-anthropomorphic devices are highly successful, such as bicycles. Non-anthropomorphic architectures open up a wide range of possibilities for the leg design as long as the exoskeleton never interferes or limits the operator (Fig. 2). Often it is difficult to develop architecture significantly different from a human leg that can still move the foot through all the necessary maneuvers (e.g. turning tight corners and deep squats). Safety issues become more prominent with non-anthropomorphic designs since the exoskeleton must be prevented from forcing the operator into a configuration they cannot reach. Another problem with this architecture is that the exoskeleton legs may collide with the human legs or external objects more often because the exoskeleton joints are not located in the same place as the human joints.

C. *Pseudo-anthropomorphic*

For maximum safety and minimum collisions with the environment, the BLEEX project chose an architecture that is almost anthropomorphic. This means the BLEEX leg is kinematically similar to a human's, but does not include all of the degrees of freedom of human legs. Additionally, the BLEEX degrees of freedom are all purely rotary joints. Since the human and exoskeleton leg kinematics are not exactly the same (merely similar), the human and exoskeleton are only rigidly connected at the extremities (feet and torso). Any other rigid connections would lead to large forces imposed on the operator due to the kinematic differences. However, compliant connections, allowing relative motion between the human and exoskeleton, are tolerable. Another benefit of not exactly matching the human kinematics is that BLEEX is easier to size for various operators.

V. DEGREES OF FREEDOM

Since BLEEX is pseudo-anthropomorphic, it has hip, knee, and ankle joints like a human, but the details of these joints differ from a human. Overall, BLEEX has seven distinct degrees of freedom per leg:

- 3 degrees of freedom at the hip
- 1 degree of freedom at the knee (pure rotation in the sagittal plane)
- 3 degrees of freedom at the ankle

The human hip is a ball and socket joint with three degrees of freedom [18]. It is natural to design a three degree-of-freedom exoskeleton hip joint such that all three axes of rotation pass through the human ball and socket hip joint. However, through the design of several mockups and experiments, we learned that these designs have limited ranges of motion and result in singularities at some human hip postures. Therefore, the hip rotation joint for both legs was chosen to be a single axis of rotation behind the person, as shown in Fig. 3; thus it no longer passes through the human's hip joint. Additionally, an alternative rotation joint was added directly above each exoskeleton leg for testing purposes. Both hip abduction/adduction and flexion/extension axes pass through the human hip joint.

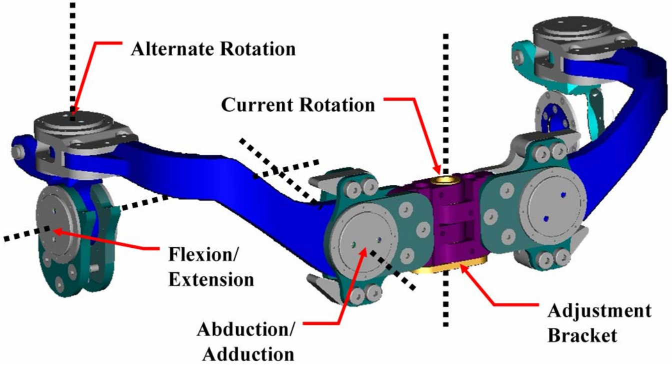

Fig. 3 BLEEX Hip Degrees of Freedom (viewed from back). Although both the abduction/adduction and flexion/extension axes pass through the center of the human hip joint, the rotation axis does not. The adjustment bracket, between the two abduction/adduction axes, is replaceable to accommodate wearers of various widths.

The human knee joint is a complex combination of rolling and sliding between the femur and tibia which allows the joint's center of rotation to move as the knee flexes [18]. Choosing a pure rotary joint for the BLEEX knee leads to simplicity and robustness, in addition to more straight forward dynamic modeling, but causes the exoskeleton knee to vary from the human's knee. Also, the BLEEX knee lacks the human knee's ability to "lock out" the leg because it does not have the moving center of rotation.

Like the human's ankle, the BLEEX ankle has three degrees of freedom. The flexion/extension axis coincides with the human ankle flexion/extension axis. For design simplification, the abduction/adduction and rotation axes on the BLEEX ankle do not pass through the human's foot and form a plane outside of the human's foot (Fig. 4).

An additional degree of freedom is added to the BLEEX foot. The front of the exoskeleton foot, under the operator's toes, is compliant to allow the exoskeleton foot to flex with the human's foot (see Section IX.B).

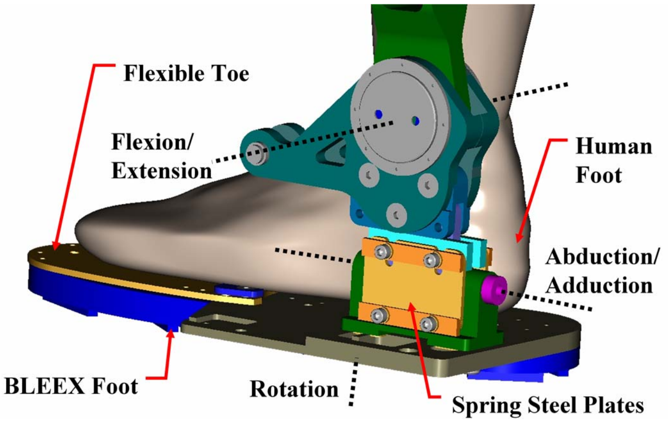

Fig. 4 BLEEX Ankle Degrees of Freedom. Only the flexion/extension axis passes through the human's ankle joint. Abduction/adduction and rotation axes are not powered, but are equipped with appropriate impedances.

VI.RANGE OF MOTION

The BLEEX kinematics are close to human kinematics, so the BLEEX joint ranges of motion are determined by examining human joint ranges of motion. At the very least, the BLEEX joint range of motion should be equal to the human range of motion during walking (shown in column 1 in Table 1), which can be found by examining Clinical Gait Analysis (CGA) data ([19] – [21]). Safety dictates that the BLEEX range of motion should not be more than the operator's range of motion (shown in Column 3 of Table 1) [22]. For each degree of freedom, the second column of Table 1 lists the BLEEX range of motion which is, in general, larger than the human range of motion during walking and less than the maximum range of human motion.

TABLE 1
BLEEX JOINT RANGES OF MOTION

	Human Walking Maximum	BLEEX Maximum	Average Military Male Maximum
Ankle Flexion	14.1°	45°	35°
Ankle Extension	20.6°	45°	38°
Ankle Abduction	not available	20°	23°
Ankle Adduction	not available	20°	24°
Knee Flexion	73.5°	121°	159°
Hip Flexion	32.2°	121°	125°
Hip Extension	22.5°	10°	not available
Hip Abduction	7.9°	16°	53°
Hip Adduction	6.4°	16°	31°
Total Rotation External	13.2°	35°	73°
Total Rotation Internal	1.6°	35°	66°

Ideally, to arrive at the most maneuverable exoskeleton, one desires to have a system with ranges of motion slightly less than the human's maximum range of motion. However, BLEEX uses linear actuators (see Section VIII), so some of the joint ranges of motion are reduced to prevent the actuators' axes of motion from passing through the joint center. If this was not prevented, the joint could reach a configuration were the actuator would be unable to produce a torque about its joint. Additionally, all the joint ranges of motion were tested and revised during prototype testing (Fig. 5). For example, mock-up testing determined that the BLEEX ankle flexion/extension range of motion needs to be greater than the human ankle range of motion to accommodate the human foot's smaller degrees of freedom not modeled in the BLEEX foot.

Fig. 5 BLEEX Mock-up used to test and revise the BLEEX degrees of freedom, ranges of motion, and ergonomics. These prototypes were built on a Fused Deposition Modeling (FDM) machine.

VII.WHICH JOINTS TO ACTUATE?

Each BLEEX leg has seven degrees of freedom (eight counting the toe flexibility), but actuating them all leads to unnecessarily high power consumption and control complexity. Instead, only joints that require substantial power should be actuated. As a first step, the actuation was designed primarily for walking, so CGA data was used to determine which degrees of freedom consume power while walking.

As expected, the highest amount of power is consumed for flexion/extension at the ankle, knee, and hip ([18], [19] – [21], Fig. 6). The ankle and hip both require significant positive power and thus need to be actuated. The knee requires mainly negative power (it absorbs power) while walking; however, when climbing steps and slopes, or squatting, the knee becomes critical for adding positive power to the system [23] (Fig. 7). Therefore, the knee joint is also actuated.

Besides the flexion/extension joints, hip abduction/ adduction requires the most power during walking since it provides the lateral balancing forces; thus, the BLEEX hip abduction/adduction joint is actuated. According to CGA data, the other degrees of freedom (hip rotation, ankle rotation, and ankle abduction/adduction) all have very small power consumptions while walking and thus remain un-actuated (Fig. 6). Fig. 8 summarizes all of the degrees of freedom chosen for the BLEEX and indicates which of these joints are powered. The un-actuated joints still may have springs, or other impedances, to reduce the load on human muscles and increase comfort.

VIII.ACTUATOR SELECTION

BLEEX is completely autonomous, carrying its own power source, so power conservation is critical for mission duration. Every effort was made to keep the exoskeleton legs, and actuators, compact and lightweight to reduce the exoskeleton's power consumption. Additionally, the power efficiency of the actuation system is crucial.

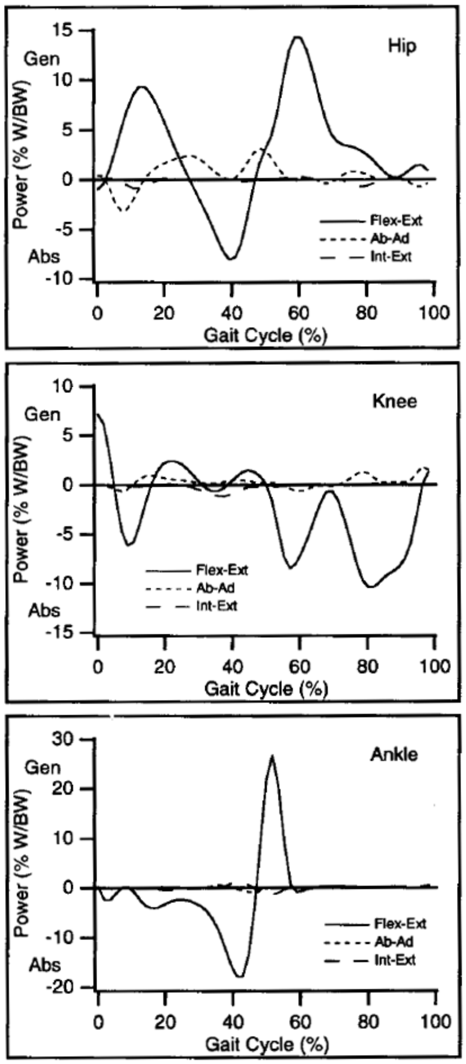

Fig. 6 Human Power Required for Walking. The most power is required by the flexion/extension joints in the ankle, knee, and hip. Besides these joints, the hip abduction/adduction requires the next most power. [18]

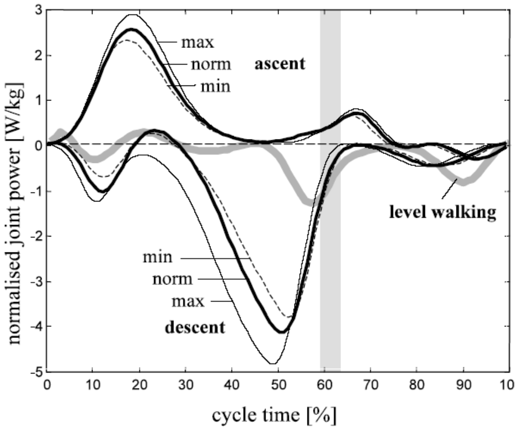

Fig. 7 Knee Power Required for Ascending/Descending Stairs. The knee requires significant power when ascending stairs (instead of absorbing power like it does during level walking) [23].

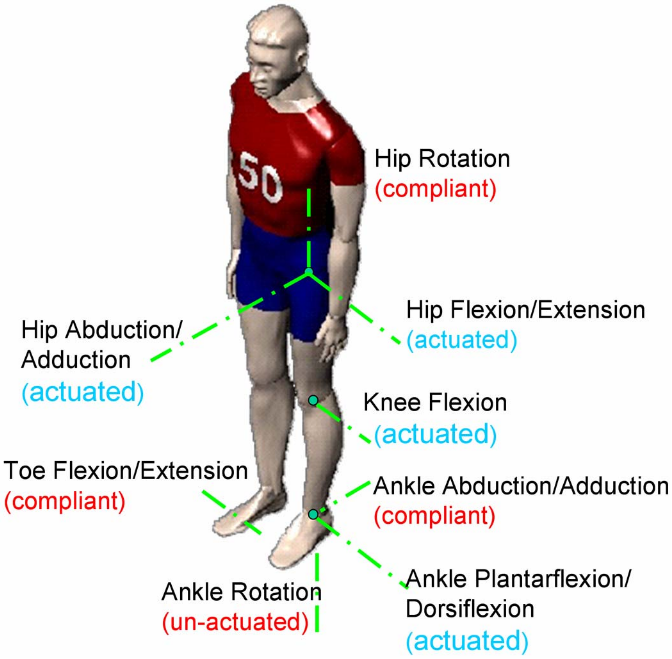

Fig. 8 BLEEX Degrees of Freedom.

Hydraulic actuators have high specific power (power to actuator weight ratio), thus are the smallest actuation option available. Also, hydraulic fluid is largely incompressible leading to a relatively high control bandwidth. However, hydraulic systems can lose a great deal of power in their servovalves due to the large pressure drops across the servovalves. BLEEX uses linear hydraulic actuators primarily because of their compact size, low weight, and high force capabilities. Rotary hydraulic actuators usually have either internal leakage or considerable amounts of friction.

Assuming a supply pressure of 6.9 MPa (1000 psi), the BLEEX actuators are sized to provide the joint torques seen in CGA data [24]. BLEEX uses 19.05 mm (0.75 inch) bore, double-acting linear piston-cylinders for all its joints. Once the actuator sizes and mounting positions were chosen to ensure the required range of motion [Table 1] and required torque [24], the joint velocity data was used to determine the average fluid flow rate required to walk. The power sources built for BLEEX all provide a constant supply pressure of 6.9 MPa (1000 psi) to the servovalves at all times, regardless of the desired actuator force and speed. Therefore, the average hydraulic power for each actuator is determined by multiplying the average flow rate by the supply pressure. For BLEEX, the ankle, knee, and hip flexion/extension joints require an average of 1.3 kW of hydraulic power to walk [24]. An additional 540 W of hydraulic power is necessary for maneuvers other than walking and for the hip abduction/adduction actuators. 4-way, double-stage servovalves were selected to control the actuators due to their high bandwidth, high flow rates, and low electrical power requirements. These valves require approximately 28 W of hydraulic power each, so the eight valves consume 224 W total. The total hydraulic power requirement for the 75 kg

BLEEX (and payload) to walk at 1.3 m/s is approximately 2.27 kW, or 3.0 hp (including a 10% safety factor) [24].

IX. BLEEX DESIGN

Fig. 9 is an overall model of BLEEX (simplified to emphasize the major components). The following sections (A – E) discuss the critical features of the major components.

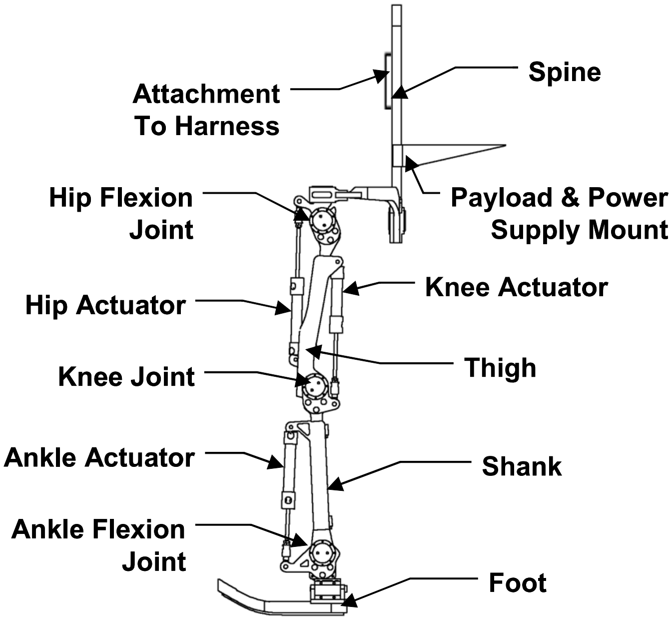

Fig. 9 BLEEX Model (simplified to emphasize major components)

A. *Powered Joint Design*

The joints of BLEEX support large forces and off-axis moments from the payload, yet have a slim profile, no play, and low friction. As shown in Fig. 10, the joint structure also encloses an encoder to protect the sensor. Two full-complement aircraft bearings (30.6 kN radial load rating) are spaced 2.5 cm apart to handle the force and off-axis moment loading. All the actuated BLEEX joints are identical, except for their actuator mount position.

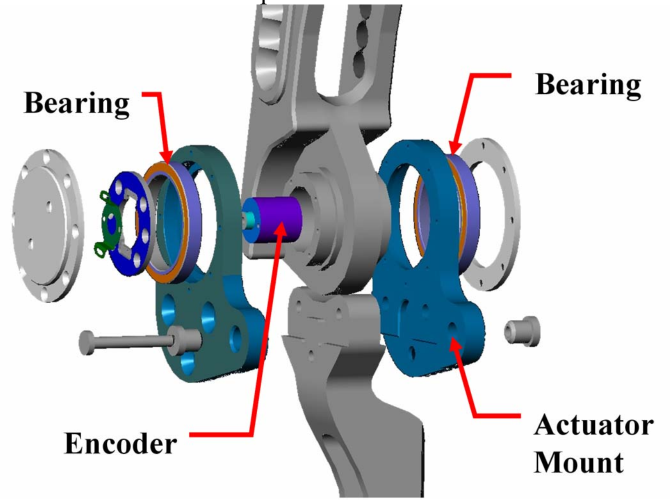

Fig. 10 BLEEX Joint Design. All actuated BLEEX Joints are designed with great precision to resist large off-axis moments and exhibit little friction while concealing the joint encoders.

B. *Foot Design*

The BLEEX foot is a critical component due to its variety of functions:

- It transfers the BLEEX's weight to the ground, so it must have structural integrity and exhibit long life in the presence of periodic environmental forces.
- It is one of two places where the human and exoskeleton are rigidly connected, so it must be comfortable for the operator. An uncomfortable connection to the human would result in an unnatural gait and unwanted forces on the operator.
- It measures the location of the foot's center of pressure and therefore identifies the foot's configuration on the ground. This information is necessary for BLEEX control [17].
- It measures the human's load distribution (how much of the human's weight is on each leg), which is also used in BLEEX control.

As shown in Fig. 11, the main structure of the foot has a stiff heel to transfer the load to the ground and a flexible toe for comfort. The operator's boot rigidly attaches to the top of the exoskeleton foot via a quick release binding. Along the bottom of the foot, switches detect which parts of the foot are in contact with the ground. For ruggedness, these switches are molded into a custom rubber sole. Also illustrated in Fig. 11 is the load distribution sensor, a rubber "pressure tube" filled with hydraulic oil and sandwiched between the human's foot and the main exoskeleton foot structure. Only the weight of the human (not the exoskeleton) is transferred onto the pressure tube and measured by the sensor. This sensor is used by the control algorithm to detect how much weight the human places on their left leg versus their right leg.

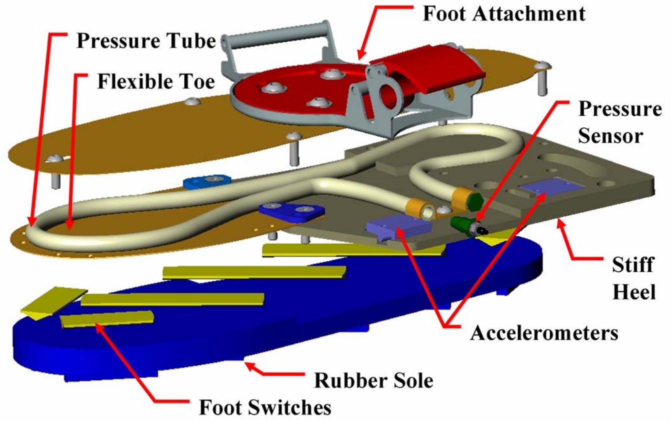

Fig. 11 BLEEX Foot Design (exploded view)

C. *Shank and Thigh Design*

The main function of the BLEEX shank and thigh are for structural support and to connect the flexion/extension joints together (Fig. 12 and Fig. 13). Both the shank and thigh are designed to be adjustable to fit people from the 5th to 95th percentile of the population; they consist of two pieces that slide within each other and then lock at the desired length.

To minimize the hydraulic routing, manifolds were designed to route the fluid between the valves, actuators, supply, and return lines. These manifolds mount directly to the cylinders to reduce the hydraulic distance between the valves and actuator, maximizing the actuator's performance. The actuator, manifold, and valve for the ankle are mounted on the shank, while the actuators, manifold, and valves for the knee and hip are on the thigh. One manifold, mounted on the knee actuator, routes the hydraulic fluid for the knee and hip actuators.

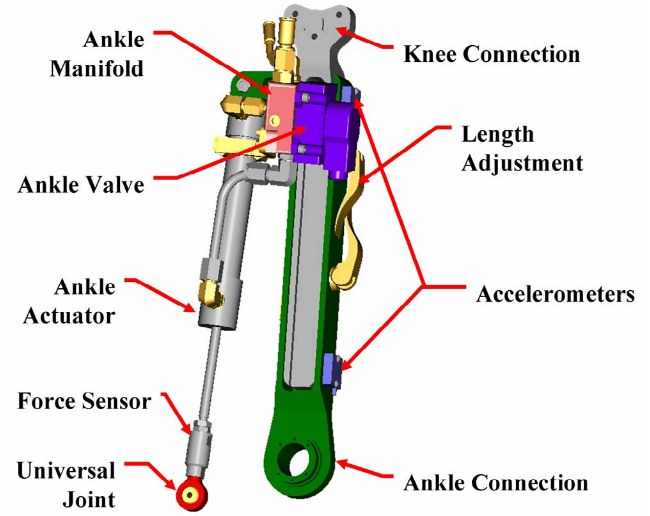

Fig. 12 BLEEX Shank Design

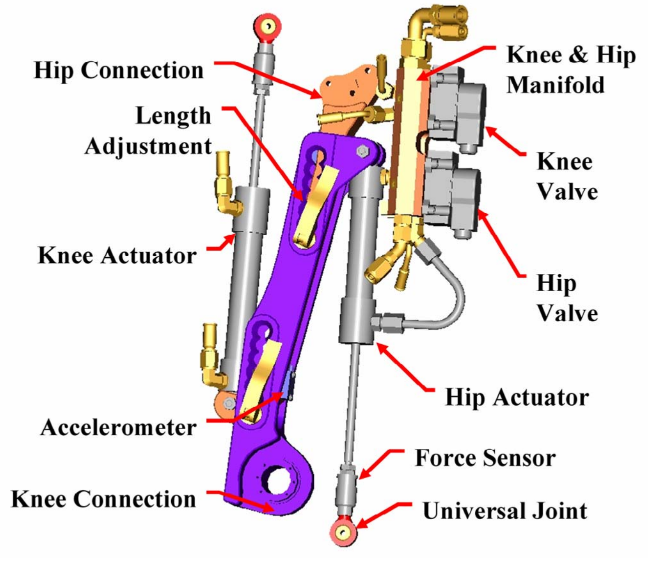

Fig. 13 BLEEX Thigh Design

D. *Torso Design*

As shown in Fig. 14, the BLEEX torso connects to the hip structure (shown in Fig. 3). The power supply, controlling computer, and payload mount to the rear side of the torso. Fig. 14 also illustrates the actuator, valve, and manifold for the hip abduction/adduction joint. An inclinometer mounted to the torso gives the absolute angle reference for the control algorithm.

Custom electronic boards (called remote I/O modules or RIOMs) are used to acquire all of the sensor data and communicate with the control computer (called the supervisor I/O module or SIOM) [25]. Some of the RIOMs along with the SIOM are attached to the BLEEX torso and illustrated in Fig. 14.

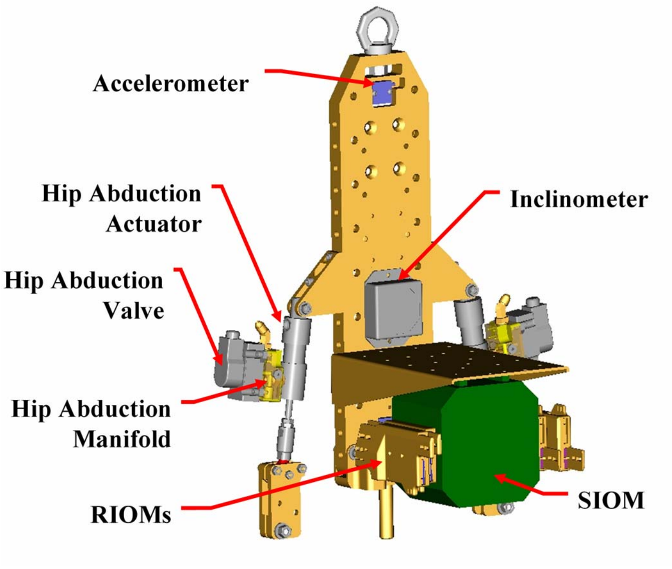

Fig. 14 BLEEX Torso Design (viewed from backside)

The front side of the torso is equipped with a harness worn by the operator. This harness (Fig. 15) is the second rigid attachment point to the operator. Generally, the harness consists of a curved, rigid back plate which attaches to the torso. It also includes comfortable backpack-like straps which grasp the operator and distribute any forces over the operator's torso, chest, shoulders, and upper back. Several harnesses were built to yield maximum comfort for the operator. Unlike harnesses for most activities, the exoskeleton harness must distribute forces and moments in any direction. Theoretically, under perfect control, only balancing loads need to be transferred between the operator and machine, but during controller development, the harness needs to withstand any possible load.

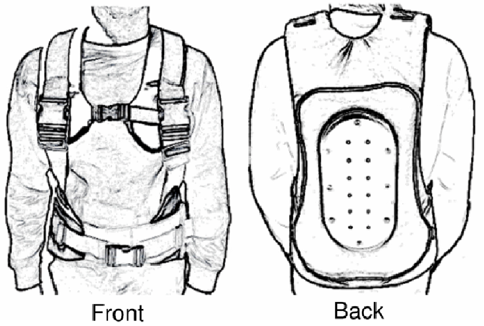

Fig. 15 Exoskeleton Harness Concept showing the shoulder and waist straps (Front) and rigid plate to attach to the exoskeleton spine (Back).

E. *Final Design*

Fig. 16 shows the current BLEEX design. The black backpack encloses the power source, controller computer, and payload.

Fig. 16 Final BLEEX Design

X. CONCLUSIONS AND FUTURE WORK

While there is still significant work remaining, BLEEX has successfully walked while carrying its own weight and producing its own power. This makes BLEEX the first energetically autonomous lower extremity exoskeleton capable of carrying a payload. Currently BLEEX has been demonstrated to support up to 75 kg (exoskeleton weight + payload), walk at speeds up to 1.3 m/s, and shadow the operator through numerous maneuvers without any human sensing or pre-programmed motions.

Current work on BLEEX includes studying differences in predicted and measured performance data and analyzing methods of increasing system efficiency. The functioning exoskeleton is an excellent platform for testing new sensors, actuation schemes, and control schemes for current and future exoskeletons. Hopefully with continued improvement to the system's fieldability, the BLEEX will become a practical method of increasing human carrying capacity and endurance through rough environments.

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