Human Power Extender:
An Example of Human-Machine Interaction via the Transfer of Power and Information Signals

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Abstract A human's ability to perform physical tasks is limited by physical strength, not by intelligence. We define "extenders" as a class of robot manipulators worn by humans to augment human mechanical strength, while the wearer's intellect remains the central control system for manipulating the extender. Our research objective is to determine the ground rules for the design and control of robotic systems worn by humans through the design, construction, and control of several prototype experimental direct-drive/non-direct-drive multi-degree-of-freedom hydraulic/electric extenders. The design of extenders is different from the design of conventional robots because the extender interfaces with the human on a physical level. Two sets of force sensors measure the forces imposed on the extender by the human and by the environment (i.e., the load). The extender's compliances in response to such contact forces were designed by selecting appropriate force compensators. This paper gives a summary of some of the selected research efforts related to Extender Technology, carried out during 80's. The references, at the end of this article, give detailed description of the research efforts.

1. Introduction

This article presents an overview of a new human-integrated material handling technology being developed at the University of California, Berkeley. This material handling equipment is a robotic system worn by humans to increase human The human becomes a part of the extender, and "feels" a force that is related to the load carried by the extender.

Figure 1 shows an example of an extender [15]. Some major applications for extenders include loading and unloading of missiles on aircraft; maneuvering of cargo in shipyards, foundries, and mines; or any application which requires precise and complex movement of heavy objects.

The goal of our research at the University of California, Berkeley, is to determine the ground rules for a control system which lets us arbitrarily specify a relationship between the human force and the load force. In a simple case, the force the human feels is equal to a scaled-down version of the load force: for example, for every 100 pounds of load, the human feels 5 pounds while the extender supports 95 pounds. In another example, if the object being manipulated is a pneumatic jackhammer, we may want to both filter and decrease the jackhammer forces: then, the human feels only the low-frequency, scaled-down components of the forces that the extender experiences. Note that force reflection occurs naturally in the extender, so the human arm feels a scaled-down version of the actual forces on the extender without a separate set of actuators.

Three elements contribute to the dynamics and control of this material handling system: the human operator, an extender to lift the load, and the load being maneuvered. The extender is in physical contact with both the human and the load, but the load and the human have no physical contact with each other. Figure 2 symbolically depicts the communication patterns between the human, extender, and load. With respect to Figure 2, the following statements characterize the fundamental features of the extender system.

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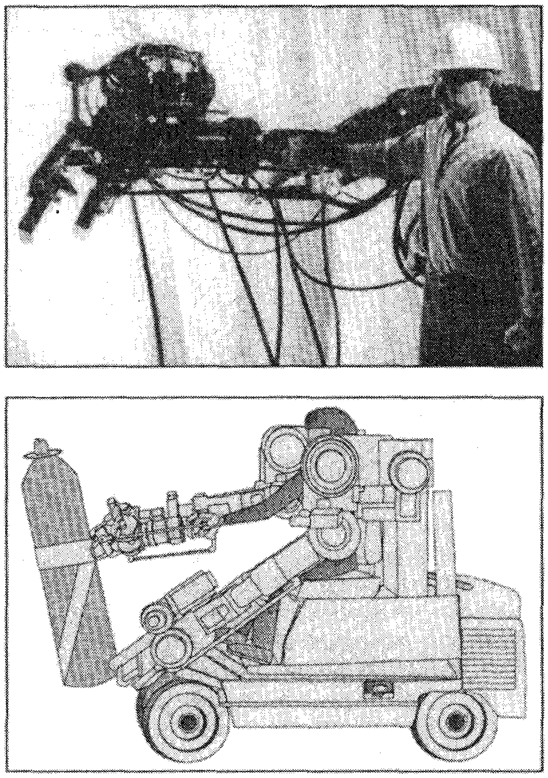


Figure 1: Experimental Six-Degree-of-Freedom Hydraulic Extender designed for loading and unloading aircrafts

1) The extender is a powered machine and consists of:1) hardware (electromechanical or hydraulic), and 2) a computer for information processing and control.
2) The load position is the same as the extender endpoint position. The human arm position is related kinematically to the extender position.
3) The extender motion is subject to forces from the human and from the load. These forces create two paths for power transfer to the extender: one from the human and one from the load. No other forces from other sources are imposed on the extender.
4) Forces between the human and the extender and forces between the load and the extender are measured and processed to maneuver the extender properly. These measured signals create two paths of information transfer to the extender: one from the human and one from the load. No other external information signals from other sources (such as joysticks, pushbuttons or keyboards) are used to drive the extender.

The fourth characteristic emphasizes the fact that the human does not *drive* the extender via external signals. Instead, the human moves his/her hands naturally when maneuvering an object.

Considering the above, human-machine interaction can be categorized into three types:

1) Human-machine interaction via the transfer of power

   In this category, the machine is not powered and therefore cannot accept information signals (commands) from the human. A hand-operated carjack is an example of this type of machine; to lift a car, one imposes forces whose power is conserved by a transfer of all of that power to the car. This category of human-machine interaction includes screw-drivers, hammers, and all similar unpowered tools which do not accept information signals but interact with humans or objects through power transfer.

2) Human-machine interaction via the transfer of information

   In this category, the machine is powered and therefore can accept command signals. An electric can opener is a machine which accepts command signals. No power is transferred between the can opener and the human; the machine function depends only on the command signals from the human [22].

3) Human-machine interaction via the transfer of both power and information signals

   In this category, the machine is powered and therefore can accept command signals from the human. In addition, the structure of the machine is such that it also accepts power from the human. Extenders fall into this category. Their motions are the result not only of the information signals (commands), but also of the interaction force with the human [11].

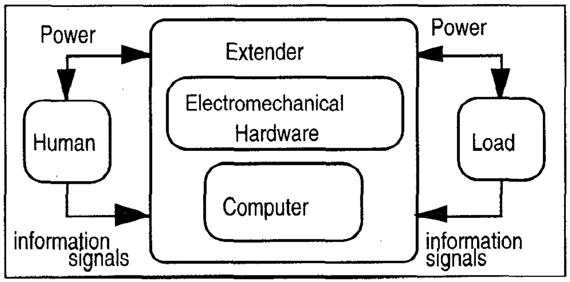


Figure 2: The extender motion is a function of the forces from the load and the human, in addition to the command signal from the computer.

Our research focuses on the dynamics and control of machines belonging to the third category of interaction involving the transfer of both information signals and power. The information signals sent to the extender computer must be compatible with the power transfer to the extender hardware. The objective of our research effort is to determine the rules for the control of robotic systems worn by humans through the design, construction, and control of a prototype experimental extender.

2. Work at UC Berkeley

It is important to note that previous systems (described in [1, 4, 5, 6, 19, 20 and 21]) operated based on the master-slave concept [16], rather than on the direct physical contact between human and manipulator inherent in the extender concept. Unlike the Hardiman and other man-amplifiers, the extender is not a master-slave system (i.e. it does not consist of two overlapping exoskeletons.) There is no joystick or other device for information transfer. Instead, the human operator's commands to the extender are taken directly from the interaction force between the human and the extender. This interaction force also helps the extender manipulate objects physically. In other words, information signals and power transfer simultaneously between the human and the extender. The load forces naturally oppose the extender motion. The controller developed for the extender translates this interaction force signal into a motion command for the extender. This allows the human to initiate tracking commands to the extender in a very direct way. The concept of transfer of power and information signals is also valid for the load and extender. The load forces are measured directly from the interface between the load and the extender and processed by the controller to develop electronic compliancy [8, 9, 10, 12, and 13] in response to load forces. In other words, information signals and power transfer simultaneously between the load and the extender [11, 14, 15]. Several prototype experimental extenders were designed and built to help clarify the design issues and verify the control theories for various payloads and maneuvering speeds.

2.1 One-Degree-of-Freedom Extender

To study the feasibility of human force amplification via hydraulic actuators, a one-degree-of-freedom extender was built (Figure 3 and 4). This experimental extender consists of an inner tube and an outer tube. The human arm, wrapped in a cylinder of rubber for a snug fit, is located in the inner tube. A rotary hydraulic actuator, mounted on a solid platform, powers the outer tube of the extender. A piezoelectric load cell, placed between the two tubes, measures the interaction force between the extender and the human arm. Another piezoelectric load cell, placed between the outer tube and the load, measures the interaction force between the extender and the load. Other sensing devices include a tachometer and encoder (with corresponding counter) to measure the angular speed and orientation. A microcomputer is used for data acquisition and control. We developed a stabilizing control algorithm which creates any arbitrary force amplification and filtering. This study led to understanding the nature of extender instability resulting from human-machine interaction [11].

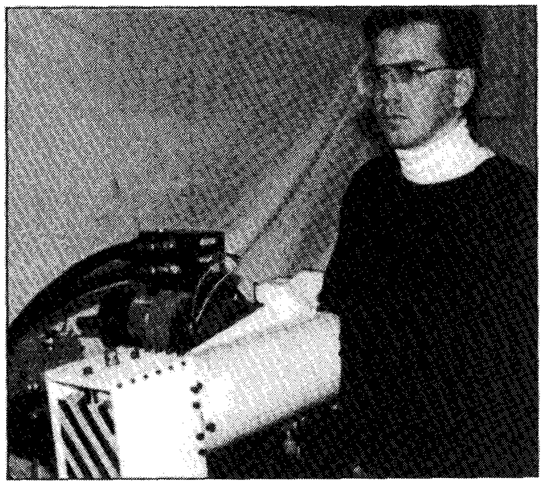


Figure 3: A one-degree-of-freedom hydraulic extender during an unconstrained maneuver.

2.2 Two-Degree-of-Freedom Direct-Drive Electric Extender

To rapidly maneuver light loads (weighing less than 50 lb), the bandwidth of the extender's actuators must be wider than the human largest maneuvering bandwidh. The dynamic behavior of the extender system at high speeds is non-linear.

To develop and test nonlinear control algorithms, a direct-drive, electrically-powered extender was built (Figure 5). The direct connection of the motors to the links (without any transmission systems) produces highly nonlinear behavior in the extender. This extender has two degrees of freedom corresponding to a shoulder and an elbow. Two motors are located at the same height as the average human shoulder. Force sensors are located at the human-extender and extender-load interfaces. A third degree of freedom may be added: either rotation about a vertical axis or roll about a horizontal fore-aft axis. Figure 5 shows the seven-bar-linkage mechanism used for our prototype laboratory system. Force sensors are mounted at the human-machine and machine-environment interfaces. Motor 2 rotates link 4 causing the main arm (link 6) to move up and down via a four-bar linkage (links 4, 5, 6, and 3 as the ground link). In another four-bar linkage (links 1, 2, 3, and 7), motor 1 rotates link 1 causing the follower link (link 3) and the main arm (link 6) to move in and out. Both motors 1 and 2 are connected to bracket 7 which is mounted on a platform at the same height as the human shoulder.

A gripper is mounted on link 6 where the operator force, is measured along two directions. When the human holds onto the gripper, his/her upper arm parallels link 3 and his lower arm parallels link 6. The materials and the dimensions of the device components are chosen to preserve the structural-dynamic integrity of the haptic interface. Each link is machined as one solid piece rather than as an assembly of smaller parts. Link 1, 3, 6 are made of high strength 7075 aluminum alloy to reduce the weight of the haptic interface device. Link 2, 4, 5 are made of steel to fit in limited design space. This study led to understanding the nonlinear stability analysis and the trade-offs between stability and performance for extenders with nonlinear behavior [17].

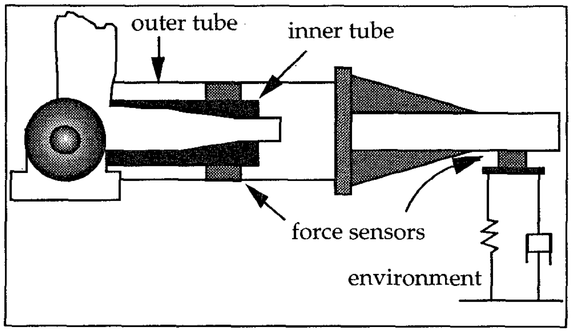


Figure 4: A one-degree-of-freedom hydraulic extender during a constrained maneuver.

2.3 A Two-Degree-of-Freedom Non-Direct-Drive System to Measure Human Arm Dynamics

We have learned from our research work that human arm dynamic behavior is the dynamic element which varies the most in human-machine systems, both from person to person and also within one person [2, 3, 7, 23].

To understand significant variations in human arm dynamics when the human wears an extender, a computer-driven XY table was designed and built for measuring the human arm dynamics in horizontal maneuvers. A piezoelectric force sensor between the handle and the table measures the human's force along two orthogonal directions. Two high-resolution encoders on the motors measure the table's motion to within two microns [14].

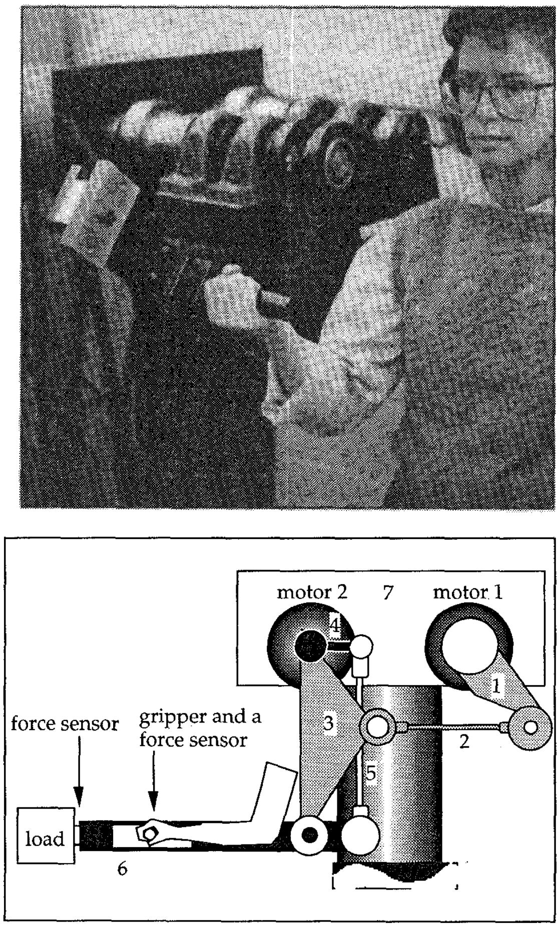


Figure 5: A two-degree-of-freedom direct-drive experimental extender to verify the feasibility of using direct-drive actuators for high-speed maneuvers of loads weighing less than 50 lb.

In a set of experiments where the table was maneuvered by a computer, the operator tried to move her hand and follow the table so that zero contact force was created between her hand and the table. Since the human arm cannot keep up with the high frequency motion of the table when trying to create zero contact forces, large contact forces would consequently be expected at high frequencies. Based on several experiments, analysis of the power spectral density of the table position and the contact forces resulted in a human arm impedance along two orthogonal horizontal directions.

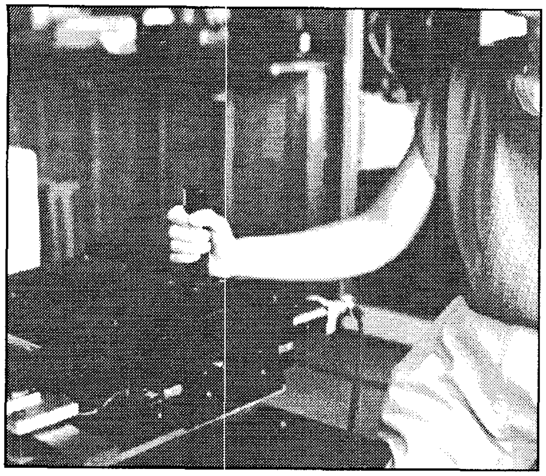


Figure 6: To understand significant variations in human arm dynamics when the human wears an extender, a computer-driven XY table was designed and built for measuring the human arm dynamics in horizontal maneuvers

2.4 Extender Walking Machine

Figure 7 shows one of our experimental walking machines which helped us learn how to control a machine that must stand on its own. This experimental machine has two links which are powered relative to each other by a DC motor. The DC motor is housed in the lower link and it powers joint 2 via a cable and speed reducer at joint 2. Joint 1 at ground level is not powered: a motor at joint 1 would require an prohibitively large and lengthy foot similar to a snow ski. We have developed an actuation mechanism and a control technique which stabilize the mass on top of the second link without the use of any gyro. The control of this *under actuated* dynamic system is the very first and very fundamental issue in the design and control of walking machines for the extender. Our results will be published in the IEEE International Conference on Robotics and Automation, 1994.

2.5 Industrial Hydraulic Extender

A six-degree-of-freedom hydraulic extender (Figure 1) was designed and built for manipulating heavy objects [15]. The extender's hand linkage performs the grasping function while the arm mechanism executes the load manipulations. The arm mechanism consists of a forearm and an upper arm and has three degrees of freedom. The rotational axes of the extender arm are designed to coincide with those of the human arm joints. Both the upper arm and the forearm are planar four-bar linkages.

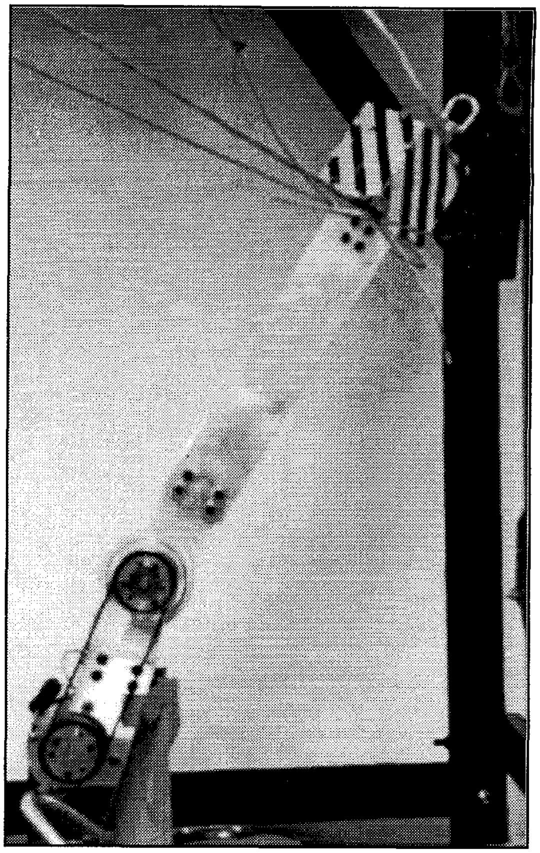


Figure 7: An experimental walking machine consisting of two links. Only joint 2 is powered. Joint 1 is not powered and sits on the ground. The goal of our research has been to stabilize this under actuated system. The actuator at Joint 2 must be controlled in such a way that the center of mass of the entire system passes through Joint 1.

Due to its complexity, the interface mechanism between the extender hand and the operator hand is not shown. The need to minimize operator fatigue requires that the extender hand be easily integrated with human hand postures. An actuator drives the axis of wrist flexion and extension. For tasks that require secure grasping, humans apply opposing forces around the object. Opposing forces in the extender hand are created by motion of the thumb relative to the wrist. The human hand is located in a glove which has force sensors mounted at the interfaces between the hand and the glove for measuring the second component of the human hand force. A thin elastic material is used at these contact points for the comfort of the human hand. The human operator can adjust the tightness of this glove simply by moving his/her elbow position horizontally. Several force sensors, not shown in the figure, are also mounted at the gripper to measure the load force in six directions. The materials and the dimensions of the extender components are chosen to preserve the structural-dynamic integrity of the extender. Each link is machined as one solid piece rather than as an assembly of smaller parts. The links are made of high strength 7075 aluminum alloy to reduce the weight of the extender.

This industrial extender is capable of lifting of objects up to 500 lb when the supply pressure is set at 3000 psi. Since the high frequency maneuvers of 500 lb load is rather unsafe, the experimental analysis on the extender dynamic behavior was carried out at low level of force amplification. In order to observe the system dynamics within the extender bandwidth, in particular the extender instability, the supply pressure was decreased to 800 psi and low force amplification ratios were chosen for analysis. This allows us to maneuver the extender within 2 Hz. Force amplifications of 7 times in the vertical direction and 5 times in the horizontal direction was prescribed on the controller. The human operator maneuvers the extender irregularly (i.e., randomly).

Figure 8 shows the FFT of the ratio of the load force to the human force along the horizontal direction where the load force is more than human force by a factor of 5. It can be seen that this ratio is preserved only within the extender bandwidth. Figure 9 shows the load force versus the human force along the horizontal direction where the slope of -5 represents the force amplification by a factor of 5. Figures 10 and 11 are similar to Figures 8 and 9, except that they show the system performance in the vertical direction. Figure 10 shows the FFT of the ratio of the load force to human force along the vertical direction where the amplification of 7 is preserved within the extender bandwidth. Figure 11 shows the load force versus the human force along the vertical direction where the slope of -7 represents the force amplification by a factor of 7.

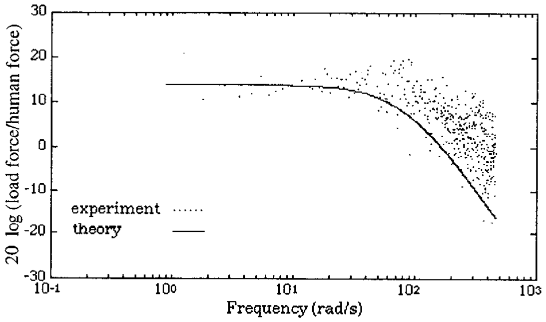


Figure 8: Theoretical and experimental force amplification ratio along the horizontal direction.

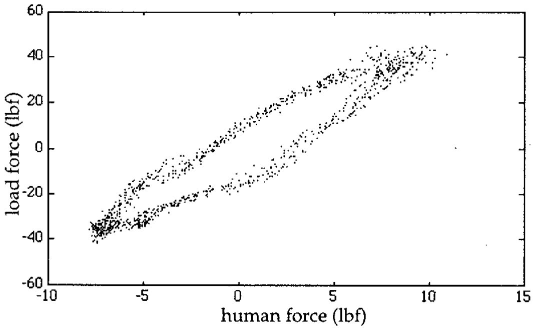


Figure 9: Load force versus human force along the horizontal direction. Slope is approximately 5.

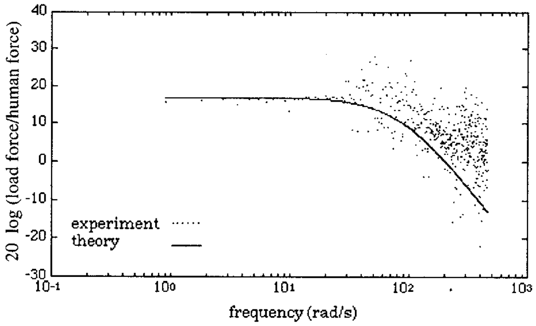


Figure 10: Theoretical and experimental force amplification ratio along the vertical direction.

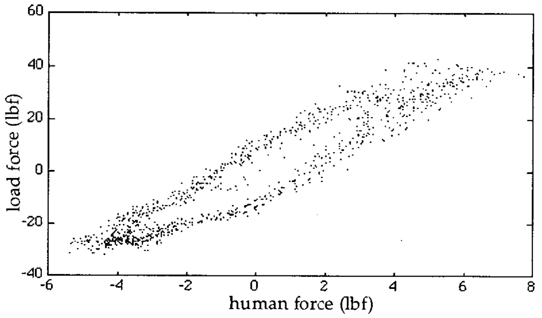


Figure 11: Load force versus human force along the vertical direction. Slope is approximately 7.

2.6 Industrial Electric Extender

An electric extender [18], composed of two arms and two legs, was designed and built for maneuvering boxes (Figure 12). Each arm has six serial joints. A molded rubber handpiece housing a piezoelectric force sensor serves as the interface between the operator and the machine. The wrist joints are unpowered and are arranged in a spherical configuration with the handpiece at the center of their axes. Thus positioning of a load is accomplished by actuation of the first three powered joints, while orientation of the end effector is achieved through wrist motions powered by the operator. The wrist has been designed to have a degenerate configuration for all possible orientations of the wrist in the targeted work envelope. Such an architecture insures that any loads applied to the end effector will not manifest themselves in moments which must be supported by the operator.

Each leg has four serial degrees of freedom, and, in this case, three additional "false" degrees of freedom are used in the interface between the operator and the machine. Similar to the those of the arm, the upper three leg joints are powered. To avoid the need of a long "foot" to support torque at the "ankle" of the machine, there are no actuators below the knee; the final degree of freedom for the leg is the rolling contact that occurs between the ankle and the ground. At the ankle, rotary and linear bearings provide degrees of freedom which are intended to isolate a foot pedal to which the operator's foot is connected through a bicycle cleat. This cleat further allows for rotary motion of the foot from side to side. A three-axis force sensor is mounted in between the foot pedal and the ankle bearing assembly. The links used in the arms and legs have been constructed from a carbon-composite material formed around a structural foam core. Aluminum inserts bonded to the composite links are used to connect each link end to its corresponding actuator. The links are curved so as to avoid interference with the operator and the rest of the machine.

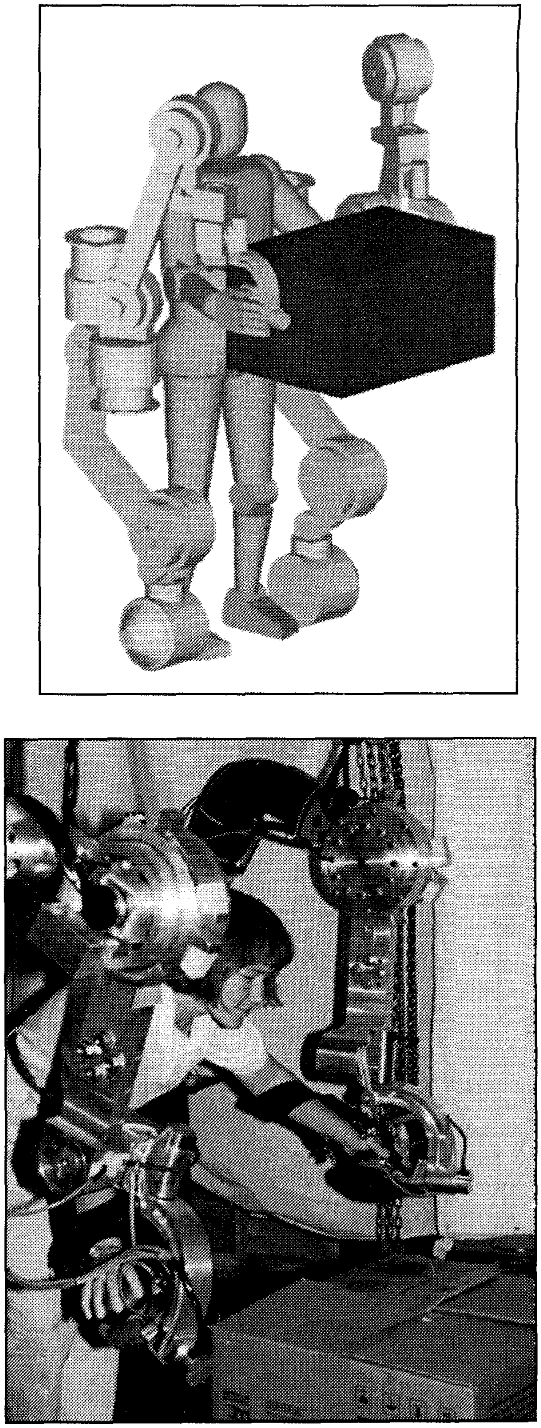
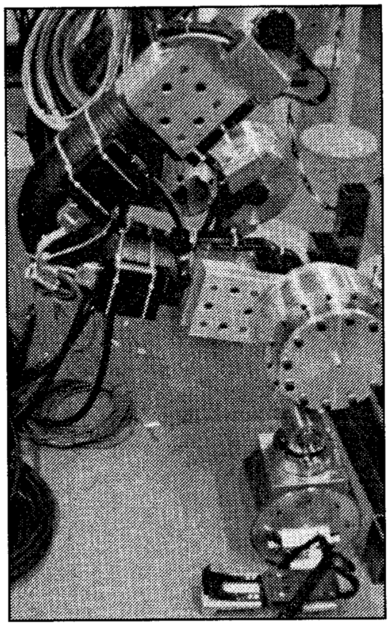
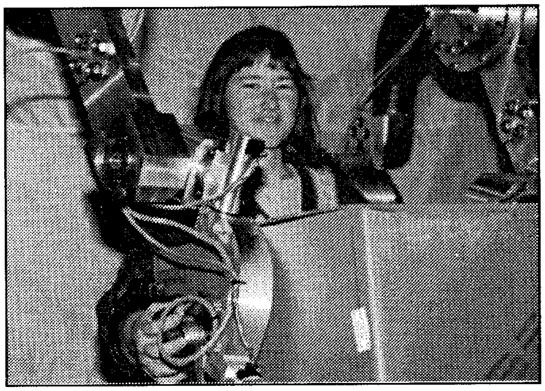


Figure 12: The electric system, designed and built at UC, Berkeley, is composed of two arms and two legs and is used to maneuver boxes in warehouses. During operation, the extender transfers to the worker's arm, as feedback, a scaled-down value of the actual load which the extender is manipulating: the worker "feels" the load weight in the manipulations. For example, for every 50 pounds of weight, a worker supports 5 pounds and the extender supports 45 pounds. In this way, the extender minimizes the risk of back injuries to workers. Commands are transferred to the extender via the contact forces between the worker and the extender, eliminating the need for a joystick, pushbutton, or keyboard to transfer such commands.





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