A Multipurpose Robotic Wheelchair and Rehabilitation Device for the Home

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Abstract — This paper describes a novel Home Lift, Position, and Rehabilitation (HLPR) Chair, designed at National Institute of Standards and Technology (NIST), to provide independent patient mobility for indoor tasks, such as moving to and placing a person on a toilet or bed, and lift assistance for tasks, such as accessing kitchen or other tall shelves. These functionalities are currently out of reach of most wheelchair users. One of the design motivations of the HLPR Chair is to reduce back injury, typically, an important issue in the care of this group. The HLPR Chair is currently being extended to be an autonomous mobility device to assist cognition by route and trajectory planning. This paper describes the design of HLPR Chair, its control architecture, and algorithms for autonomous planning and control using its unique kinematics.

I. Introduction

Reference [1] says "today, approximately 10 percent of the world's population is over 60; by 2050 this proportion will have more than doubled" and "the greatest rate of increase is amongst the oldest old, people aged 85 and older." She follows by adding that this group is subject to both physical and cognitive impairments more than younger people. These facts have a profound impact on how the world will maintain the elderly independent as long as possible from caregivers. Both physical and cognitive diminishing abilities address the body and the mental process of knowing, including aspects such as awareness, perception, reasoning, intuition and judgment. Assistive technology for the mobility impaired includes the wheelchair, lift aids and other devices, all of which have been around for decades. However, the patient typically or eventually requires assistance to use the device; whether it's someone to push them in a wheelchair, to lift them from the bed to a chair or to the toilet or for guiding them through cluttered areas. With fewer caregivers and more elderly, there is a need for improving these devices to provide them independent assistance.

Wheelchairs

There has been an increasing need for wheelchairs over time. L.H.V. van der Woude [2] states that mobility is fundamental to health, social integration and individual well-being of the humans. Henceforth, mobility must be viewed as being essential to the outcome of the rehabilitation process of wheelchair dependent persons and to their successful (re-)integration into society and to a productive and active life. Thrun [3] said that, if possible, rehabilitation to relieve the dependence on the wheelchair is ideal for this type of patient to live a longer, healthier life. Van der Woude continues stating that many lower limb disabled subjects depend upon a wheelchair for their mobility. Estimated numbers for Europe and USA are respectively 2.5 million and 1.25 million. The quality of the wheelchair, the individual work capacity, the functionality of the wheelchair/user combination, and the effectiveness of the rehabilitation program do indeed determine the freedom of mobility.

Patient Lift

Just as important as wheelchairs are the lift devices and people who lift patients into wheelchairs and other seats, beds, automobiles, etc. The need for patient lift devices will also increase as generations get older. When considering if there is a need for patient lift devices, several references state the positive, for example:

- "The question is, what does it cost not to buy this equipment? A back injury can cost as much as $50,000, and that's not even including all the indirect costs. If a nursing home can buy these lifting devices for $1,000 to $2,000, and eliminate a back injury that costs tens of thousands of dollars, that's a good deal," [4]
- 1 in every 3 nurses become injured from the physical exertion put forth while moving non-ambulatory patients; costing their employers $35,000 per injured nurse. [5]
- 1 in 2 non-ambulatory patients fall to the floor and become injured when being transferred from a bed to a wheelchair. - [6]
- "Nursing and personal care facilities are a growing industry where hazards are known and effective controls are available," said OSHA Administrator John Henshaw. "The industry also ranks among the highest in terms of injuries and illnesses, with rates about 2 1⁄2 times that of all other general industries..." [7]
- "Already today there are over 400,000 unfilled nursing positions causing healthcare providers across the country to close wings or risk negative outcomes. Over the coming years, the declining ratio of working age adults to elderly will further exacerbate the shortage. In 1950 there were 8 adults available to support each elder 65+, today the ratio is 5:1 and by 2020 the ratio will drop to 3 working age adults per elder person." [8]

In 2005, NIST ISD began the Healthcare Mobility

Project to target this staggering healthcare issue of patient lift and mobility. ISD researchers looked at currently available technology through a survey of patient lift and mobility devices [9]. That report showed that there is need for technology that includes mobility devices that can lift and maneuver patients to other seats and technology that can provide for rehabilitation to help the patient become independent of the wheelchair.

An additional area investigated in the survey was intelligent wheelchairs. NIST has been studying intelligent mobility for the military, transportation, and the manufacturing industry for nearly 30 years through the Intelligent Control of Mobility Systems (ICMS) Program. [10] Toward a standard control system architecture and advanced 3D imaging technologies, as being researched within the ICMS Program, and applying them to intelligent wheelchairs, NIST has begun outfitting the HLPR Chair with computer controls. Although throughout the world there are or have been many research efforts in intelligent wheelchairs, including: [11, 12, 13, 14] and many others, the authors could find no sources applying standard control methods nor application of the most advanced 3D imagers prototyped today to intelligent wheelchairs. Therefore, NIST began developing the HLPR Chair to investigate these specific areas of mobility, lift and rehabilitation, as well as advanced autonomous control.

This paper includes an in depth review of the HLPR Chair design in it's current stage including sections covering the structure and mobility design, patient lift, placement on other seats, rehabilitation, and control. Conclusions, future work sections, and references close the paper.

II. HLPR Chair Structure and Mobility Design

The HLPR Chair [15] prototype, shown in Figure 1, is based on a manual, steel, inexpensive, off-the-shelf, and sturdy forklift. The forklift includes a U-frame base with casters in the front and rear and a rectangular vertical frame. The lift and chair frame measures 58 cm (23 in) wide by 109 cm (43 in) long by 193 cm (76 in) high (when not in the lift position) making it small enough to pass through even the smallest, typically 61 cm (24 in) wide x 203 cm (80 in) high, residential bathroom doors. The HLPR Chair frame could be made lighter with aluminum instead of steel.

The patient seat/stand mechanism is a double, nested and inverted L-shape where the outer L is a seat base frame that provides a lift and rotation point for the inner L seat frame. The L frames are made of square, aluminum tubing welded as shown in the photograph. The outer L is bolted to the lift device while the inner L rotates with respect to the seat base frame at the end of the L as shown in Figure 1. The frames rotation point is above the casters at the very front of the HLPR Chair frame to allow for outside wheelbase access when the seat is rotated π rad (180º) and is the main reason access to other seats is available. Drive and steering motors, batteries and control electronics along with their aluminum support frame provide counterweight for the patient to rotate beyond the wheelbase. When not rotated, the center of gravity remains near the middle of the HLPR Chair. When rotated to π rad (180º) with a 136 kg (300 Lb) patient on board, the center of gravity remains within the wheelbase for safe seat access. Heavier patients would require additional counterweight.

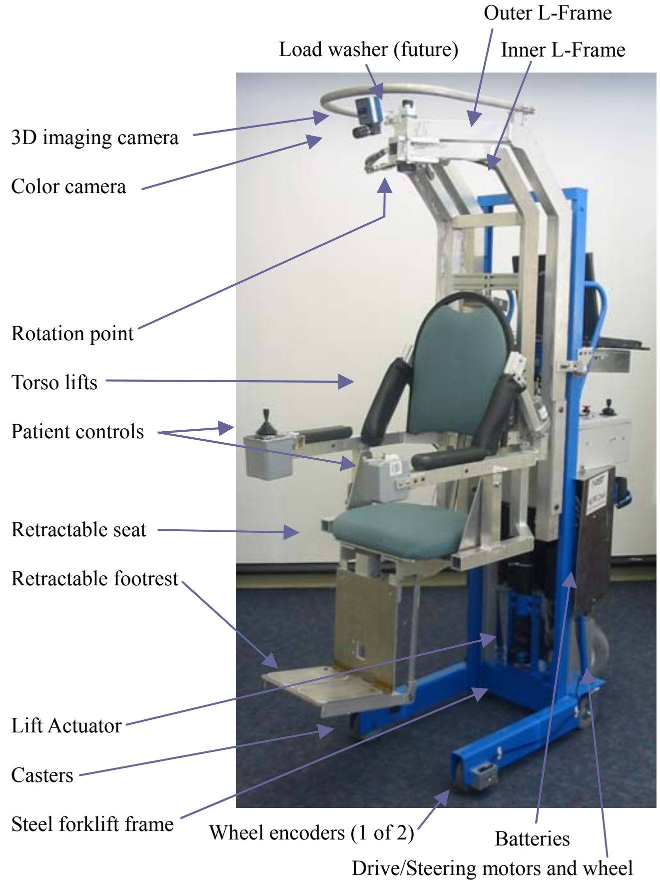

Figure 1 –Photograph of the HLPR Chair prototype.

The HLPR Chair is powered similarly to typical powered chairs on the market. Powered chairs include battery powered, drive and steer motors. However, the HLPR Chair has a tricycle design to simplify the need to provide steering and drive linkages and provide for a more vertical and compact drive system design. The drive motor is mounted perpendicular to the floor and above the drive wheel with chain drive to it. The steering motor is coupled to an end cap on the drive motor and provides approximately π rad (180º) rotation of the drive wheel to steer the HLPR Chair. The front of the robot has two casters mounted to a U-shaped frame.

The prototype drive motor is geared such that its high speed drives a chain driven wheel providing further speed reduction. HLPR Chair speed is 0.7 m/s (27 in/s). While this is sufficient speed for typical eldercare needs, a more powerful motor can replace the drive motor for additional speed.

Steering is a novel single wheel design hard stopping the wheel at just beyond π rad (180º) for safety of the steering system. Steering is reverse Ackerman controlled as joystick left rotates the drive wheel counterclockwise and joystick right rotates the drive wheel clockwise. The steering rotation amount can be limited by the amount of drive speed so as not to roll the frame during excessive speed with large steering rotation. The navigation and control of the vehicle under this novel rear wheel steer and drive is currently under study and will be described in later publications.

For access to the HLPR Chair and for mobility, the HLPR Chair is lowered as shown in Figure 2. A seat belt or harness will be required for eldercare occupant safety. For access/exit to/from the HLPR Chair, the footrest can be retracted beneath the seat. For mobility, the footrest is deployed to carry the feet. Also, manually rotated feet pads can be deployed to provide a wider footrest. When retracted, the footrest pads automatically rotate within the footrest volume.

Figure 2 – Photographs of the HLPR Chair in the mobility configuration showing the side view (left) and front view relative to a typical doorway (right).

III. Patient Lift

Patient lift is designed into the HLPR Chair to allow user access to high shelves or other tall objects while seated. The HLPR Chairs' patient lift (see Figure 3) is approximately 1 m (36 in) to reach what a typical, standing 2 m (6 ft) tall person could reach. This is a distinct advantage over marketed chairs and other concepts. [15]. The additional height comes at no additional cost of frame and only minimally for actuator cost.

Lift is achieved by a 227 kg (500 Lbs) max. lift actuator that can support 681 (1500 Lbs) statically on the HLPR Chair prototype. The actuator can be replaced with a higher capacity unit if needed. The actuator connects to a lift plate with a steel chain that is fix- mounted at one end to the HLPR Chair frame and to the lift plate at the other end. The actuator pushes up on a sprocket of which the chain rolls over providing 1 m (36 in) lift with only a 0.5 m (18 in) stroke actuator. The outer L-frame is then bolted to the lift plate. Rollers mounted to the lift plate roll inside the HLPR Chair vertical C-channel frame.

Figure 3 – HLPR Chair prototype shown in the patient lift position.

IV. Placement on Other Seats

It is estimated that 1 in 3 nurses or caregivers will develop back injuries [9]. Most injuries occur because the patient is relatively heavy to lift and access to them is difficult when attempting to place the patient onto another seat. Wheelchair dependents have difficulty moving from a seat, to their wheelchair and back without a caregivers help or other lift mechanisms. The HLPR Chair was designed with the patient lift, as explained previously, to not only access tall objects, but to also pick up and place the patient in other chairs, on toilets, and on beds.

Figure 4 shows the concept of placing a patient onto a toilet. Figure 5 (left) shows the HLPR Chair prototype in the rotated position and Figure 5 (right) shows it in the torso support position similar to the Figure 4 (center and right) graphic.

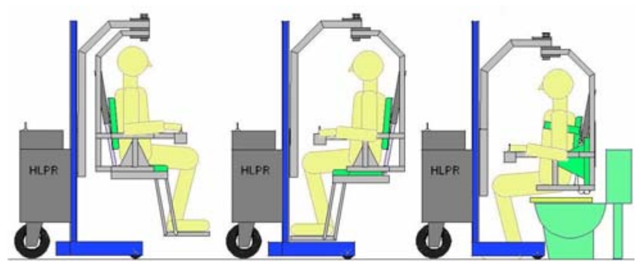

Figure 4 – Graphic showing the concept of placing a patient onto a toilet or chair with the HLPR Chair. *The patient drives to the target seat (left), manually rotates near or over the seat (middle) while the torso lifts support the patient and the seat retracts, and then is lowered onto the seat - toilet, chair or bed (right)*

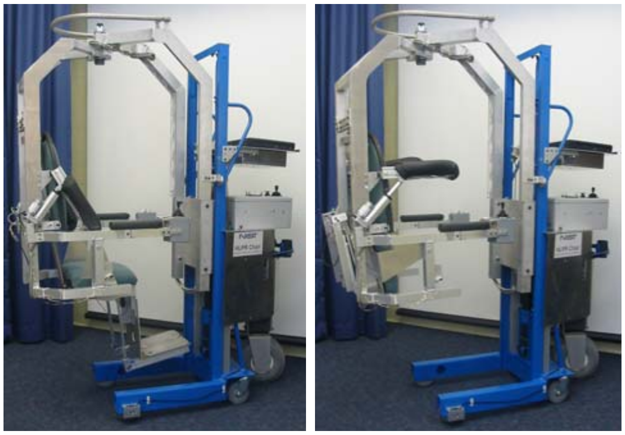

Figure 5 – Photographs of the HLPR Chair in the same positions as in the center and right Figure 4 graphics placing a person on another seat.

To place a HLPR Chair user on another seat, they can drive to for example, a toilet, seat, or bed. Once there, the HLPR Chair rotates the footrest up and beneath the seat and the patients feet are placed on the floor personally or by a caregiver. The HLPR Chair inner L-frame can then be rotated manually with respect to the chair frame allowing the patient to be above the toilet. Padded torso lifts then lift the patient from beneath his/her arm joints similar to crutches. The seat, with the footrest beneath, then rotates from horizontal to vertical behind the patients back clearing the area beneath the patient to be placed on the toilet, seat, bed, etc.

Once the person is placed on a toilet, the HLPR Chair can remain in the same position to continue supporting them from potential side, back or front fall. However, when placing a person onto a chair, the HLPR Chair must lift the patient and the patient manually rotates the chair from around the patient and out of the patients space. The HLPR Chair could then be conceptually driven from the seat location, using radio frequency or through voice commands, to a charging or waiting location and out of the patients view. When requesting to be picked up again, the patient could conceptually call the HLPR Chair remotely and have it return to the same pick up location and reverse the seat placement procedure.

V. Manual Control

The HLPR Chair controls include a joystick that sends drive controls to power amplifiers that control the drive and steering. The patient lift actuator is also controlled with the same type power amplifier through a rocker switch.. A lever switch is used to control seat and footrest retraction or deployment.

The footrest, seat and torso lift actuators are direct controlled switched forward and reverse from the battery through momentary rocker switches. Actuators for the footrest and each torso lift have 8cm (3 in) stroke while the seat includes a 31 cm (12 in) actuator to rotate it from seated to behind the back and vice versa.

Behind the seat and frame and above the drive/steer wheel is the electronics box that houses the controls for the HLPR Chair while also providing a "Nurse" or caregiver control panel that duplicates the patient controls at the seat. The Nurse control panel (see Figure 6) includes all the control functions for a nurse or caregiver to drive or lift a dependent patient. Control redundancy is designed into the HLPR Chair to also allow a caregiver to quickly gain control of the device as needed. A "Nurse/Patient" switch on the Nurse control panel allows switching between the rear (Nurse) controls and the chair (Patient) controls.

VI. Towards Autonomous Control

Recently, the HLPR Chair was modified (see figure 6) to include encoders, attached between its' frame and front caster wheels, a computer and computer interface electronics. The encoder design included adapting a shaft to one side of each caster wheel, passing it through a bearing attached to the frame and to an encoder. Although the encoder and housing add an additional 2.5 cm (1 in) to each side of the base, the overall HLPR Chair base width is still within the chair-frame width and therefore, within the overall HLPR Chair width of 58 cm (23 in). The encoders provide 3600 pulses per revolution allowing relatively fine measurement over a 12.7 cm (5 in) diameter caster wheel or approximately 90 pulses/cm (230 pulses/in) of linear travel. The relatively high measurement accuracy of the wheels will support development of accurate path planning and control algorithms for the HLPR Chair.

Included in the "Nurse" control panel is a computer/manual switch. While switched in manual mode, all of the "Nurse" - labeled (rear) controls on the box or on the "Patient" - labeled (chair) can be used. While in computer control, drive and steer are controlled by an onboard computer. The computer is currently a personal computer (PC) laptop interfacing to off-the-shelf input/output (I/O) devices housed in the box beneath the PC and connected through a universal serial bus (USB) interface. This design was chosen as a simple developer interface to the HLPR Chair prototype knowing that the computer and its interfaces can be significantly reduced in size as future commercial versions are designed. Software drivers for the HLPR Chair drive and steer control were written in C++ under the Linux operating system.

This low level control is now ready to add planned HLPR Chair navigation and obstacle avoidance control. NIST and the University of Delaware (UD) are teaming to use the NIST standard software control architecture for intelligent machines called "4D/RCS (4 dimensional/ Real-time Control System)" and UD's robot behavior generation. [17] NIST has recently applied 4D/RCS to a Defense Advanced Research Project Agency (DARPA) Project called LAGR (Learning Applied to Ground Robots). [18] The 4D/RCS structure developed for LAGR is shown in figure 7. The basic premise of the 4D/RCS columns of boxes are to sense the environment around the robot (left column), to place the sensed information into a world model (middle column), then plan and generate appropriate navigational paths and input these paths into the robot actuators in real time (right column). The horizontal rows of 4D/RCS boxes stack from a servo level control (bottom row) to grouped pixels, a lower resolution map, and a higher level planner (top row).

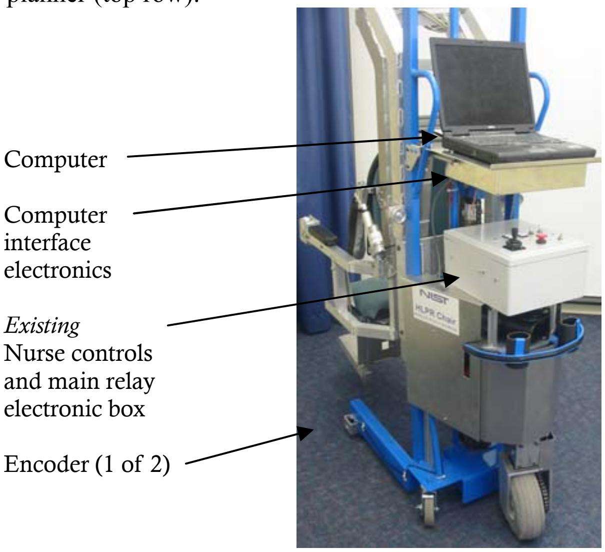

Figure 6 – Photograph of the HLPR Chair with recently added front wheel encoders, development computer and interface electronics, and advanced 3D imaging camera and color camera (cameras are shown in Figure 1).

The authors plan to adopt this standard control architecture on the HLPR Chair so that advanced 3D imagers, such as the ones shown in figure 1, and robust control algorithms can be plug-and-played to address the variety of patient mobility controls that may be needed. An earlier version (from the one pictured in figure 1), 3D imaging camera was mounted on an early version of the HLPR Chair and a control algorithm was developed and tested (see Figure 10). Results of this test, as explained in [16], clearly show detected obstacles in the vehicle path and a planned path around the obstacles.

VII. Patient Rehabilitation

HLPR Chair enhances patient rehabilitation through a load sensor and control on the lift actuator, as described in [19]. The authors designed rehabilitation into the HLPR Chair to allow, for example, stroke patients to keep their legs active without supporting the entire load of the patients body weight. The patient, once lifted, could walk while supported by the HLPR Chair driving at a slow walking pace towards regaining leg control and eliminating the need for a wheelchair.

To accomplish rehabilitation, the HLPR Chair includes, as explained in the Placement on Other Seats section, footrest and seat rotate behind the patient while he/she is lifted with torso lifts. However, instead of being placed low on a seat, the patient lift continues to move up lifting the patient as they move their legs beneath them to standing position. The HLPR Chair's open U-frame base allows access to the floor directly beneath the patient for standing. Figure 8 shows a photograph of the prototype in this configuration and a concept of how the HLPR Chair can be used for patient rehabilitation.

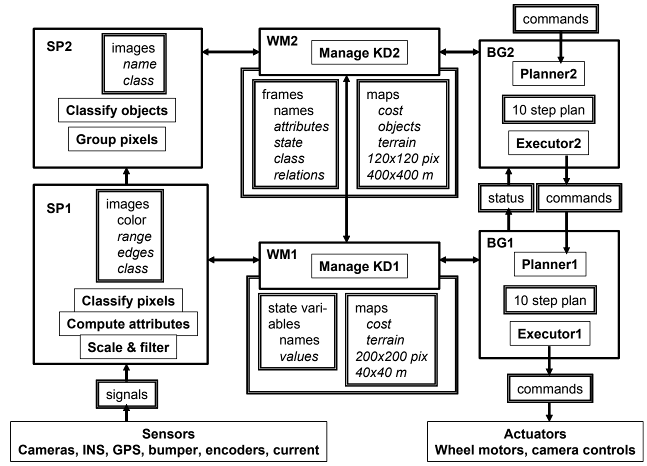

Figure 7 – NIST 4D/RCS 2-level, hierarchical control architecture developed for the DARPA LAGR Project and planned for implementation on the HLPR Chair.

Additionally, the patient can be continuously monitored with a load washer at the L-frames rotation point. The patient could adjust the amount of load he/she wishes to place onto their legs and on the floor by rotating a dial on the controls from 0- 100 percent. Load control is a future concept to be applied to the HLPR Chair prototype in the next several months.

VIII. Conclusions and Future Research

The HLPR Chair was designed to be a revolutionary patient lift and mobility system for wheelchair dependents, the elderly, stroke patients, and others desiring or even requiring personal mobility and lift access. The system shows promise for moving these groups of patients into the work force and removing the burden placed on the healthcare industry. The system has been prototyped to show the basic concept of such a patient lift and mobility system. The HLPR Chair was built to demonstrate its' relatively inexpensive capabilities to the healthcare industry and to build on it's capabilities with robust controls for mobility and rehabilitation in the near-term.

Autonomous mobility control using the 4D/RCS standard control architecture and advanced 3D imagers is planned for a next step while teaming with the University of Delaware under a federal grant. Force loading for rehabilitation of patient legs will also be studied in the near term. Collaborations for proving the service capabilities and evaluating performance of the HLPR Chair to the healthcare industry are being pursued and expected in the near future.

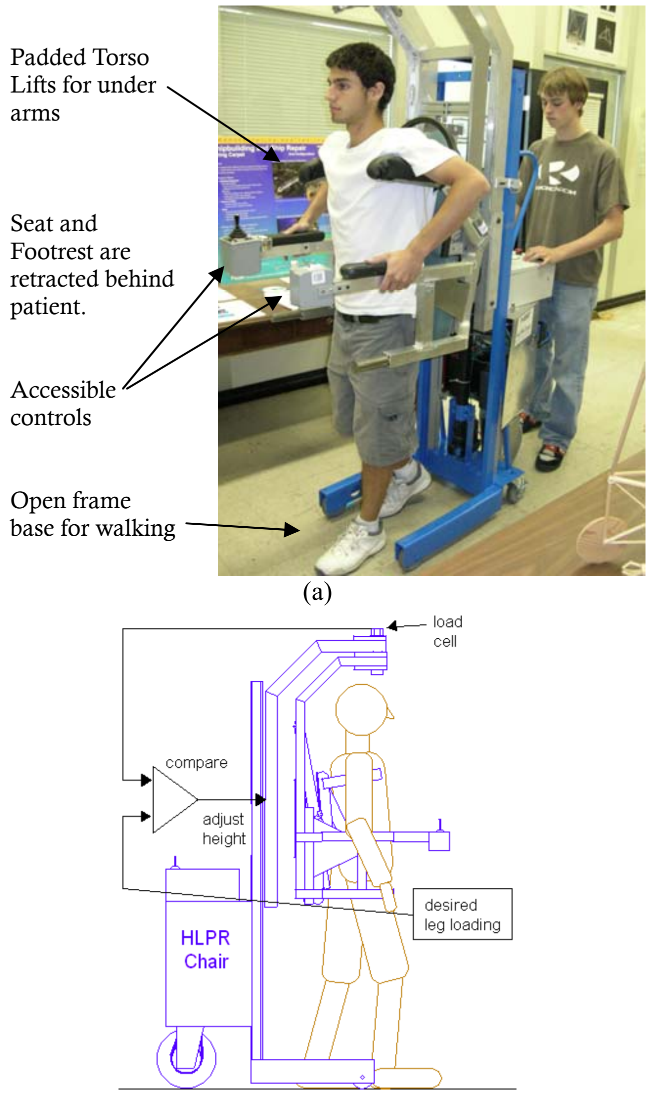

Figure 8 – (a) Photograph of the HLPR Chair prototype in the rehabilitation/walking configuration. Summer Interns (Alex Page and Robert Vlacich) demonstrate the patient and nurse configuration as part of their official duties. (b) Graphic showing the concept of how the HLPR Chair can be used for patient rehabilitation and incorporate future legs load control.

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