EXOSKELETON

1. GENERAL DESCRIPTION OF THE EXOSKELETON

The Exoskeleton (Figure 1 is a semi-active assistive robotic system that consists of a flexible torso structure coupled at the hips to long leg braces (Figure 2).

Figure 1 : Exoskeleton

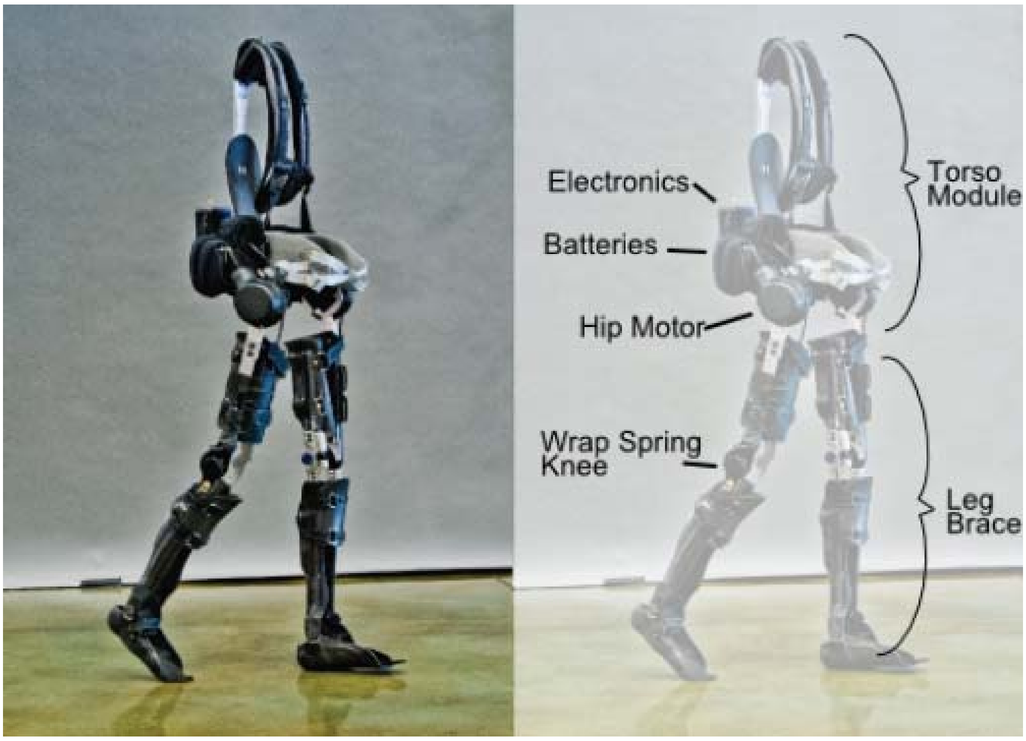

Figure 2 : Modular elements of the Exoskeleton

The system is developed to minimize weight while maintaining maximum manouvrability.

VELAS LARGAS, HEALTH CARE EQUIPAMENT
Rua Dr. António Martins, Número 44, 2º Esq, Benfica, Lisboa, na freguesia de São Domingos de Benfica, Portugal
Email: info@velaslargas.com
Website: www.velaslargas.com

- It helps people with total or partial deficit gait caused by various diseases:
  - Traumatic events
  - Degenerative deseases
  - Neoplasms
- It allows to stand-up from sitting and viceversa, to walk and drive vehicle: everything in complete autonomy.
- It allows to stay upright the patient (without the aid of crutches) and lets the hands free (Figure 3).

Figure3: Example of freedom of motion - leaning a crutch nearby to get hands free or getting into a car and stowing crutches nearby

Motors provide power at the hips while brakes at the knees govern when the knees are locked (to support weight) or unlocked (to swing freely).
Batteries and computers are located near the waist of the system where they are out of the way.
Crutches or a walker are used for balance, and the user commands the device through a wireless crutch mounted interface.
The Exoskeleton weight is about 13 Kg and its battery allows for 4 hours of continuous walking. The gait is commanded via crutch mounted controller.

The Exoskeleton is comprised of several modular elements which can be configured depending on severity of user injury. The Exoskeleton allows for size and flexibility adjustment in order to adapt to body dimensions and improve user performance. Walking speed varies with user ability, however through hardware and control refinement, comfortable walking speed is about 0.48m/s.
The Exoskeleton is designed to bridge the gap between seated and standing operation by assisting the user in a new range of postures.
This approach expands pilot capabilities while seated and increases overall utility as a tool.
Consistent standup and sit-down enables individuals to be self-sufficient with the possibility of full operation without a spotter.

VELAS LARGAS, HEALTH CARE EQUIPAMENT
Rua Dr. António Martins, Número 44, 2º Esq, Benfica, Lisboa, na freguesia de São Domingos de Benfica, Portugal
Email: info@velaslargas.com
Website: www.velaslargas.com

The Exoskeleton requires some form of stability aid for balance. This means that this machine is only useful for individuals with complete motor control of their arms and enough torso control to assist with overall balance.
This device is not necessarily contraindicated for high level (upper thoracic) paraplegics: however, these individuals will require additional assistance during training and operation.

2. EXOSKELETON DESCRIPTION

The Exoskeleton consists of functional modules that can be used separately (Figure 4).

Hip Module

Knee Module

Standard AFO

Figure 4 : Exoskeleton modular architecture

2.1.1 Hip Module

- Hip Module is autonomous and self-sufficient
- The support can be adjusted according to individual needs
- Compensates for the total or partial paralysis of the flexor muscles of the hip and buttocks, caused by spinal cord injuries and diseases of various kinds such as post-polio syndrome, stroke and multiple sclerosis
- Provides assistance in flexion extension that without hindering movement during each step. It allows to synchronize the parameters of step during walking.

2.1.2 Knee Module

- Knee Module compensates the weakness or paralysis of the quadriceps, partial lesions of the spinal cord, the post-polio syndrome and multiple sclerosis
- Replaces "smartly" the common joint locking
- The impediment is controllable in response to flexion during stance
- Does not prevent the extension
- Does not prevent flexion and extension during swing.

2.2 FULL TORSO FRAME

The Exoskeleton can be configured to have a full torso frame for users with lesser abdominal control, which is commonly associated with higher injury levels. The extended torso frame adopts an aluminum "spine" and shoulder straps. Figure 5 shows the extended torso module.
The spine of the module can be adjusted in length and in stiffness to accommodate different user preferences.
Furthermore, the torso frame can also be adjusted for different user hip widths. An optional corset can be attached onto the exoskeleton spine for even more trunk support if necessary. However, so far none of the test pilots needed to use the corset.

Figure 5 : Test of Extended Torso Frame (Left) - Demonstration of use of the corset and walker (Right)

2.3 ADJUSTABLE LEG MODULE

An adjustable leg module was tested to fit test pilots who do not have custom molded leg braces. The length of the leg module can be adjusted at the femur link and at the tibia link so that the device can be worn by users ranging from 152 cm tall to 188 cm.

The module can also be adjusted for different amounts of hip rotation and ankle plantar flexion and dorsiflexion. The human-machine interface of the leg module consists of a thigh brace, a calf brace, and an exoskeleton shoe.

2.4 DESIGN FOR INTEGRATION WITH A WHEELCHAIR

An important feature of the Exoskeleton is to allow easy donning and doffing while remaining seated in one's wheelchair.

The exoskeleton breaks down into three components (torso, right and left legs), all light enough to be manipulated and adjusted from a wheelchair as illustrated in Figure 6. This approach differs from old designs where the exoskeleton remains fully assembled at all times. The modular approach obviates the need for the user to perform a sitting pivot transfer from his/her wheelchair into the exoskeleton (illustrated in Figure 7).

Sitting pivot transfers require that the pilot have substantial upper body strength and control in order to lift and pivot themselves from the wheelchair into the adjacent exoskeleton. By eliminating the sitting pivot transfer requirement, the exoskeleton is made accessible to a broader user group.

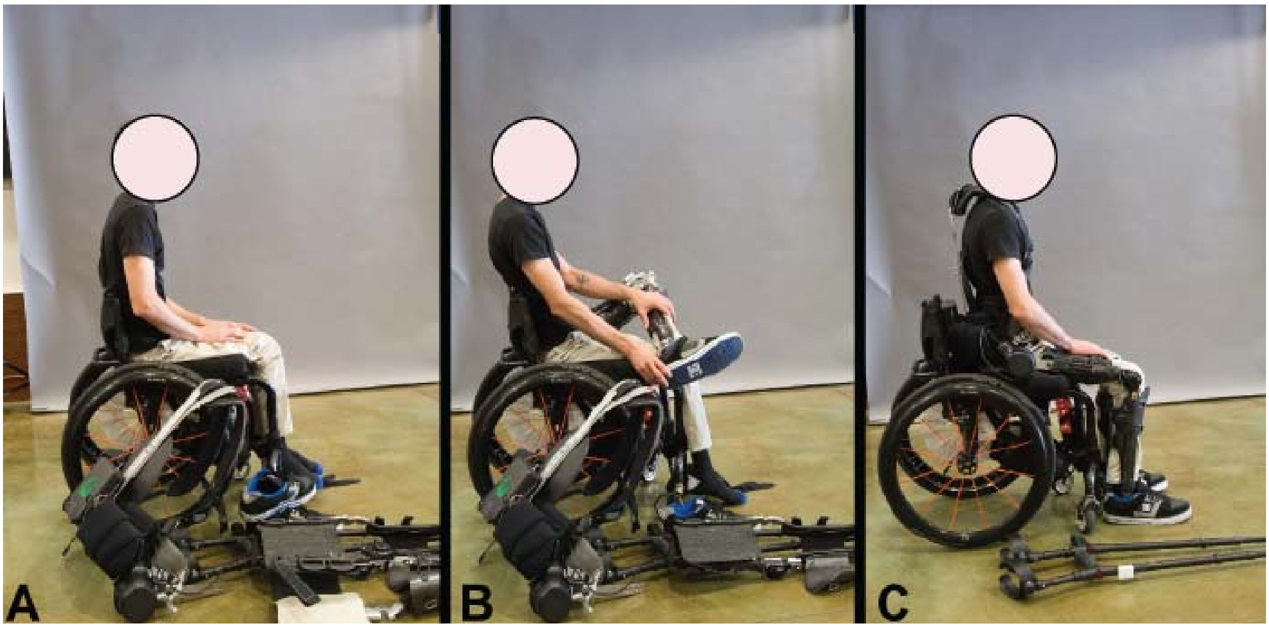

Figure 6: Exoskeleton integration with a Weelchair - Quick assembling around the pilot - A) Components laid out. B) Leg Braces attached. C) Torso Connected

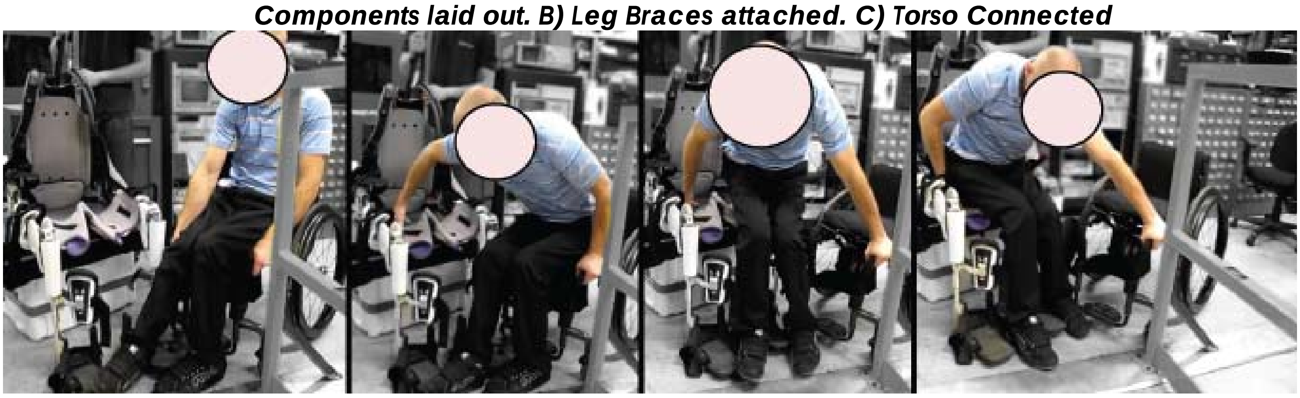

Figure7: Pilot performing a sitting pivot transfer to get into the Exoskeleton from a wheelchair.

VELAS LARGAS, HEALTH CARE EQUIPAMENT
Rua Dr. António Martins, Número 44, 2º Esq, Benfica, Lisboa, na freguesia de São Domingos de Benfica, Portugal
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Website: www.velaslargas.com

3. EXOSKELETON OPERATION AND USER INTERFACE

3.1 THE FINITE STATE MACHINE

The operation of the Exoskeleton is governed by the finite state machine (FSM) illustrated in Figure 8.
All states are accessed through the use of a wireless crutch mounted User Interface (UI) consisting of a forward button and a backward button (illustrated in Figure 9). The FSM can be imagined as set of options arranged in two dimensions so that the pilot has at most two choices at any given time (move forward or move backward through states). States are changed through the forward and backward buttons.
Some additional gating conditions in the form of verification clicks and time constraints are in place to avoid accidental state changes. Additionally, it is important to ensure that the pilot does not fall backwards during standup.
Currently, this failure mode is avoided by measuring absolute torso angle during standup through the use of a torso mounted Inertial Measurement Unit (IMU).

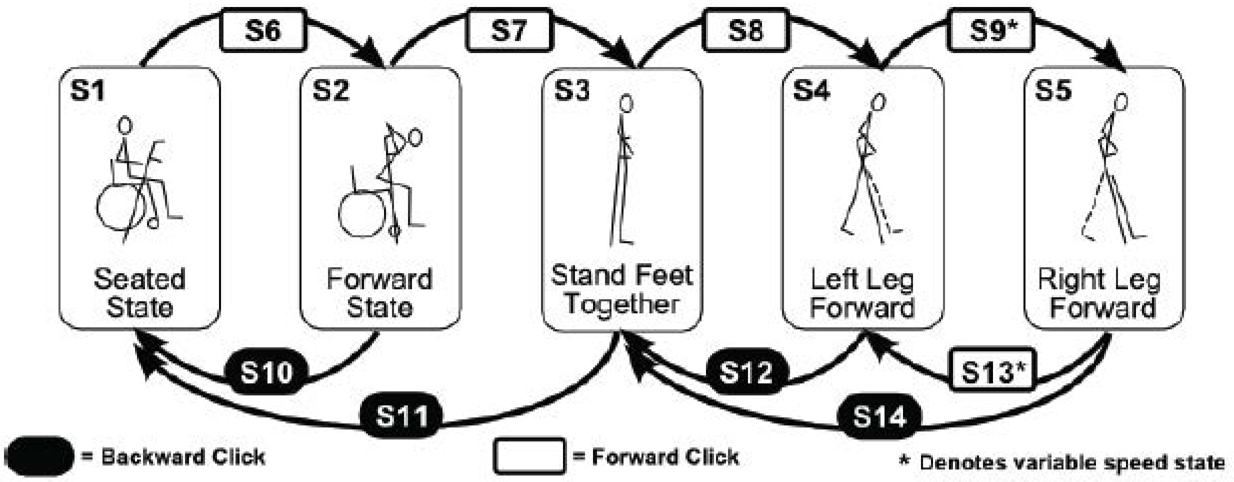

Figure 8: Exoskeleton finite state machine

States S9* and S13*(Right Foot Swing and Left Foot Swing respectively) are special states that can command a plurality of possible hip trajectories to enable variable speed walking. States S9* and S13*are gated by a Forward Click with the condition that the last step was taken less than 15 seconds previously (this ensures that the user cannot accidentally trigger a step while standing and talking).
Walking starts with speed Vo (time since last step is > than Time Threshold).
As long as steps are triggered at a rate slower than the Time Threshold, S9* and S13* will remain in Vo. If steps are triggered at a rate faster than the Time Threshold, velocity will increase with each step until maximum velocity is achieved. If steps are triggered at a rate slower than the Time Threshold, velocity will return to Vo.
The system for variable speed walking was designed with the assumption that paraplegic pilots are either navigating tightly constrained environments (offices, kitchens, etc.) requiring tight control and low speed, or traversing larger distances (hallways, sidewalks, etc.) requiring high speed and less control over step placement.

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Rua Dr. António Martins, Número 44, 2º Esq, Benfica, Lisboa, na freguesia de São Domingos de Benfica, Portugal
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Website: www.velaslargas.com

Figure 9: User Interface embedded in forearm crutch

4.2 GUARDING AGAINST UNWANTED STATE CHANGES
To avoid accidental motions, several state changes shall be gated by additional conditions.

4.1.1 Standing
It is often convenient for a pilot to talk or work while standing in place. The FSM automatically locks against state changes after 15 seconds of inactivity to avoid accidental steps. This allows the pilot to let go of the crutches so that he/she can be hands free. To unlock the FSM the pilot presses the forward button, waits 1 second and then presses the forward button again.
An audible tone shall be implemented to confirm that the FSM is successfully unlocked.

4.1.2 Stand to Sit
To command sit-down the pilot must press and hold the back button for more than 1 second, wait for audible feedback, release the button, and then confirm the command.

4.1.3 Sit to Stand
To command stand-up the pilot must press and hold the forward button for more than 1 second, wait for audible feedback, release the button, and then confirm the command. Additionally, if the pilot's torso angle moves out of a safe range during stand-up, the system will make an audible tone and automatically transition back to sitting. This avoids the possibility of falling backwards while standing up.

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