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Abstract— **As an increase in average age of population is expected, there is growing interest in devices to help mobility. These should be light, energy efficient, modular and comfortable. Therefore, XoSoft EU project is developing an assistive soft exoskeleton for lower limbs targeting, among others, elderly patients using soft modular quasi-passive actuators. The prototype is described and validated on a post-stroke patient, evaluating Stride Length, Step Length Asymmetry and Hip/Knee Range of Motion.**

Keywords—**Exoskeletons, Soft Robotics, Assistive Device.**

I. Introduction

THE total amount of over-60 population is foreseen to grow up to 2 billion people by 2050, with over-80 as the fastest growing profile [1]. World Health Organization (WHO) organizes Regional Frameworks to promote *Healthy Ageing* defined as *"the process of developing and maintaining the functional ability that enables wellbeing in older age"*. One key-point of the functional abilities is the capacity to be mobile. WHO recommends different solutions in [1] to address the problem of mobility impairment (which is caused by changes, in both physical and mental capabilities, environment and elderly attitude), one of these is to provide assistive technologies to aid mobility. In addition to a natural decrease in mental and physical capabilities for elderly, there is an increasing rate of survival after severe diseases [2] (such as stroke or incomplete Spinal Cord Injuries SCI); those patients need equipment to regain mobility, as well. Walking-aid devices consist, mostly, of passive equipment like canes or walkers. Passive devices cannot provide any additional external assistance when needed by the user. Active devices such as Robot Suit HAL 5, Ekso and ReWalk [3] provide a solution to assist total and partial SCIs and post-stroke patients, but they could also be used by frail elderly. Actual active devices, though, are often bulky, uncomfortable, heavy and potentially unsafe. Moreover, rigid links does not accommodate the complicate biological joint movements, resulting in a complex redundant design.

All these aspects decrease end user acceptance thus preventing further mass adoption of wearable active walk assistive devices. A solution is a soft approach to wearable devices [4], which are more comfortable, lighter and easier to don and doff. XoSoft is a EU funded project which aims to develop a soft and modular lower body assistive device; targeting as its Primary Users (PUs) frail elderly, post stroke and incomplete SCI patients [5]. The project follows a User Centred Design (UCD) approach, as shown in Fig. 1. User requirements and design specification are established before the concept technology development starts [6]. In addition, the on-board sensors collect data to monitor the health status of PUs; in this way, XoSoft allows continuous monitoring of PUs key parameters and analysis by Secondary Users (SU) such as physicians, medical doctors or relatives, and Tertiary Users (TU) such as health insurance companies or social welfare. XoSoft relies on Quasi-Passive Actuators (QPA), providing an assistive force harvesting and storing energy in the passive elastic modules, during precise moments of the patient's gait, then releasing it when needed [7]. This actuation approach, together with a soft exoskeleton design, results in a more comfortable, lighter and configurable wearable device. In this paper, is presented an evaluation of the Beta-1 prototype gait-aiding performances. In section II of this paper, the prototype of the assistive wearable device is described. The tested device is in a unilateral configuration to support the right part of the lower body, aiding affected hip and knee joints. In section III, the sensors of the systems, detailed definition of testing protocol, evaluation metrics and results are presented. Finally, conclusions and further improvements of the device based on these findings, are described in section IV.

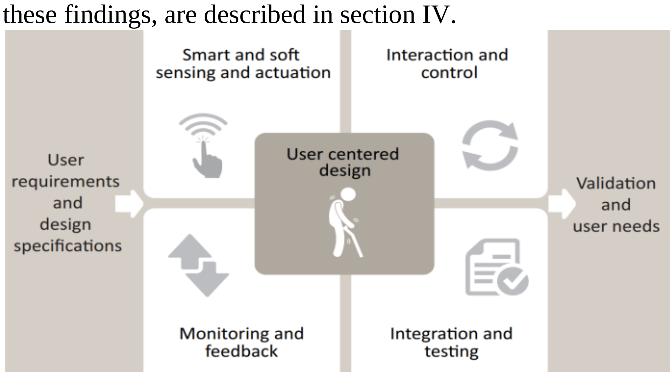

Figure 1 Picture shows how XoSoft UCD is central to all activities

II. Beta-1 XoSoft design

The development was guided by the UCD approach, focused on PUs needs in terms of improvements in autonomous mobility, wearing comfort and device usability [6].

The following features are the result of UCD procedures:

- Usability;
- Maintenance, Repair and Cleaning;
- Charging and Storage;
- Smart Capabilities.

The current Beta-1 Prototype is composed of garment, waist belt and a backpack containing the main control unit; even if

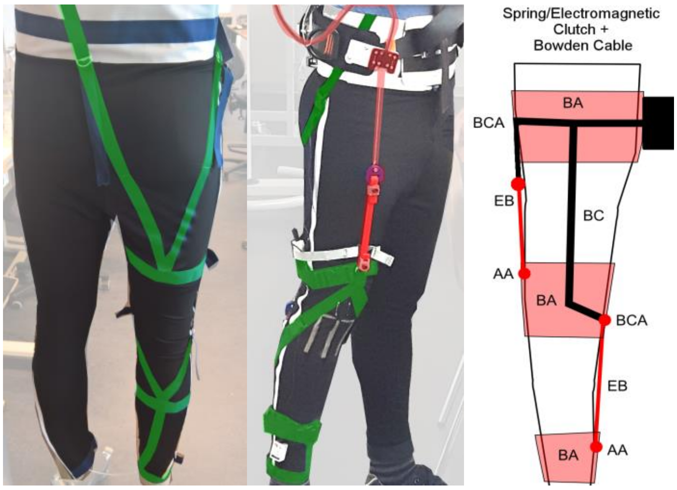

Figure 2 Front and Rear view of the Beta-1 prototype garment and placement of the actuation system. BC = Bowden Cable, EB = Elastic Band, BA = Body Attachment, AA = Actuator Attachment, BCA = Bowden Cable Attachment. In the prototype the BA and BCA are highlighted in green, EB and BC are highlighted in red.

in a prototyping phase, most of the UCD requirements are already implemented.

A. Garment

The current garment version is mainly focused on usability features, as they are the most important at this stage of development. In particular, zippers and snap-lock buckles were chosen as the most efficient fixing mechanism for users with lower body impairment. Zippers on the whole leg length allow fast donning and doffing, while buckles adjust the quasi passive actuation system attachment points.

The geometry of the anchor points was chosen to deliver assistive torque to hip and knee, without sacrificing wearer's comfort. Indeed, as it is shown highlighted in green in Fig. 2, webbing of inextensible fabric was used as reinforcement to unload forces and distribute pressure in the widest possible area of skin, avoiding bruises or other skin damages. Frail elderly and post stroke patients have fragile skin or low epidermal sensitivity, both of which can lead to skin redness or pressure ulcers, dropping the device user acceptance.

B. Actuation Principle

The assistive force is delivered by QPA. This kind of mechanism cannot apply a non-conservative motive force, instead it stores mechanical energy in passive elements (e.g. springs, elastic bands). In this prototype, the active elements are two commercial electromagnetic clutches (111-06-13G, Miki Pulley Co. Ltd, Kanagawa, Japan) (Fig. 3), and the passive ones are latex EB (Loop Band, Fit Point, Brescia, Italy) (highlighted in red in Fig 2). The clutches are homed in a safety harness belt and connected to the EBs by mean of BC, as it is shown in Fig. 2. One end of the EB is attached to the reinforced fabric on the trousers, the other is attached to the BC and is free to move. BC sheaths are secured to the reinforced supports, too. When a clutch is engaged, the EB it is not free to move, so it elongates harvesting energy from both active muscular activity and limb inertia, releasing it when clutches disengage. EB final length is determined by the clutch engaging time, assistive force depends on EB stiffness and elongation. The clutches have an elastic string to pull back the BC, to not slack the EBs. A formal mathematical description of QPAs is provided in [7].

As described in [7] and preliminary validated in [8], the QPA hip module design is guided by an optimization of the engage/disengage time, elastic constant and attachment position to maximize metabolic energy saving. The knee module is designed based on the test subject's needs, that is to it assists knee flexion to avoid foot drop, where EB acts mainly as a damper.

C. Control and Sensing

This version of XoSoft equips two wireless pressure sensitive insoles made of FSRs (1-Inch ShuntMode, Sensitronics, Bow, USA) (Fig. 3) and casted in foam to fit the test subject. The sensorized insoles are used for gait segmentation, providing Toe Off, Heel Strike and Flat Foot signals for both feet to the control algorithm. The main control board is a microcontroller board (LaunchPad XL, Texas Instruments, Dallas, US) with a shield which provides power management (Fig. 3), enhanced communication capabilities (Wi-Fi and CANopen) and high-power outputs for the clutches, while the firmware runs the control loop at 100 Hz. The electronics is housed in a backpack. The control algorithm engages/disengages the EBs on a gait percentage basis without any software delay and the clutches block within 2 ms after power is applied. The gait percentage for the hip QPA engagement is provided by an optimization procedure [7], while the knee is assisted during the initial swing phase that helps avoiding foot drop. Only signals from gait segmentation were used to control clutches, due to high variability in gait spatio-temporal parameters of hemiparetic patients [9].

Additional Tech IMU V4 series sensors (Technaid, Madrid, Spain) (Fig. 3) are used to reconstruct subject's movements.

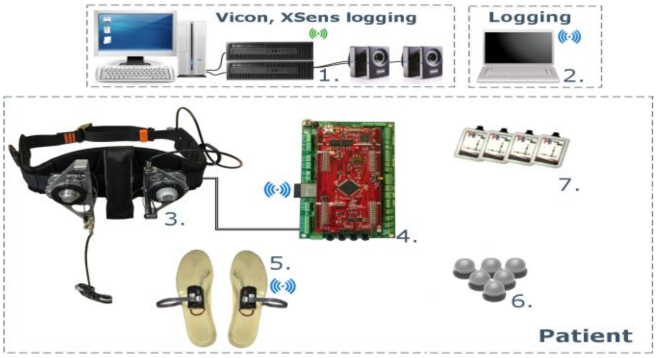

Figure 3 Control and sensing electronics of Beta-1 prototype. (1) central logging system. (2) custom client software for the insoles and main control board. (3) safety belt to home the clutches. (4) main control board (5) pressure sensor insole. (6) Vicon markers. (7) IMUs

III. XoSoft Beta-1 Experimental assessment

Beta-1 prototype has been tested with a 68 years old male post-stroke patient (details in Table I). The cerebrovascular stroke

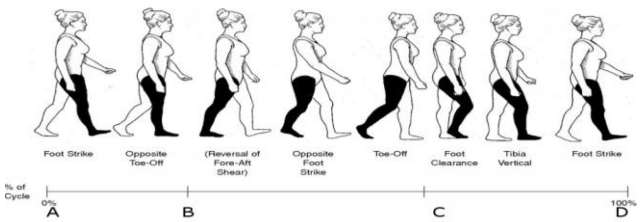

Figure 4 Gait cycle and points of activation and deactivation of clutches (adapted from [11])

was experienced in 2011. He has a unilateral impairment of the right part of his body. The trials took place at the Institute of Physiotherapy of ZHAW, tests and investigation protocols (BASEC-Nr. 2016-01406) have been approved by local ethical committee (Kantonale Ethikkomission Zürich, Zürich, Switzerland) and the subject signed informed written consent. The prototype has been tailor-made to assure a perfect fit, avoiding misalignments and loosening effects of the trousers.

TABLE I
TEST SUBJECT DETAILED INFORMATION

Gender	male
Age	68 years
Height	170.0 cm
Weight	72 Kg
Foot Size	26.5 cm
Walking Speed	0.59 m/s
Inside leg length to floor	81.0 cm
Leg length iliac crest to floor	102.0 cm
Impairment	Hemiparesis

A. External Sensors

A 3D high-speed camera system (Vicon Vantage V5, Vicon Motion Systems Ltd, Oxford, UK), was used to monitor subject's movements. The system's sampling rate is 240 Hz, three or four retro-reflective markers were placed on: forefoot, rearfoot, shank, thigh, pelvis, trunk (Fig. 3). In combination with the Vicon system, two AMTI force plate sensors (OR6-7-2000, AMTI Inc, Watertown, US) recorded ground reaction forces at 1200Hz. The calibration of the system was performed with a static trial and four functional ones, thus defining the coordinate system of the segments based on the standards of International Society of Biomechanics [10]. Subject speed was monitored by mean of two photocells (Witty, Microgate, Bolzano, Italy).

B. Experimental Protocol

The subject was asked to walk at a self-defined speed without exoskeleton for five trials, which were recorded by the photocells, for calibration. Then, the subject was instructed to walk at the same calibrated speed straight back and forth on a 10 m path, ten times for each different test setup (control strategy). 3D video data and ground reaction forces were used to reconstruct the joints angles, step length and stride. The force plates were located in the middle of the path. Time synchronization of optical tracking, force plate systems with the exoskeleton's main control board is achieved by means of an external signal of the common logging system (Fig. 3). The detailed information about the testing setup is included in Table II. EB final length differs from gait cycle to another, in Table II there is the final length maximum value. The control strategies implemented have been chosen based on [7] and to contrast foot drop of this subject, augmenting the maximum knee flexion angle during initial swing phase.

TABLE II
TEST INFORMATION

Trials		10
Control Strategy	0 1 2	No XoSoft, Clutches always active, Clutches deactivate after 70ms toe off
EB Stiffness		950 N/m
EB initial/final length		13/17 cm
Max Assistive Force		40 N
Power		24V, 3700mAh LiPO
Total Weight		4,8 Kg

Different strategies were used:

- No XoSoft as a reference for data analysis
- Clutches always active (from 0% to 100% of gait Fig. 4, mark A to D)
- Clutches activated during midstance (~15% of gait Fig. 4, B mark), deactivated after 70ms toe off (~70% of gait, Fig. 4, C mark)

In every evaluated trial, both the used elastic bands had the characteristic listed in Table II.

C. Metrics

Before any analysis, optical data was filtered using a low-pass Butterworth filter (4th-order) with a cut-off frequency of 7 Hz (kinematic) and 400 Hz (kinetics). All data recorded during trials that showed visibility problems, were discarded. This paper focuses on performance evaluation of Beta-1 prototype regarding PU's gait kinematics. For each trial k the following indexes are used:

- Step Length Asymmetry, defined as
$$SLA_k = 1 - \frac{X_u}{X_a} \tag{1}$$
where X_u is the step length of the unaffected leg, while X_a is the step length of the affected one.
- Stride length, calculated as
$$S_k = X_r + X_l \tag{2}$$
where $X_r,\ X_l$ are step length of right and left foot.
- Range of Motion of Hip and Knee joints (HRoM, KRoM) angles in Sagittal plane
$$\{H,K\}RoM_k = \frac{1}{N}\sum_N^{i=0} max\_flex_i - min\_flex_i \tag{3}$$
where max_i and min_i are *i-th* maximum and minimum of the knee and hip joint flexion angle
- Peak Knee and Hip Flexion (PKF, PHF) angles in Sagittal plane
$$PKF_k = \frac{1}{N}\sum_N^{i=0} max\_kneeflex_i \tag{4}$$
$$PHF_k = \frac{1}{N}\sum_N^{i=0} max\_hipflex_i \tag{5}$$
where N is the amount of maximum flexion angles in one trial

D. Results

The indexes show how the subject-exoskeleton interaction alters the user's movements. As Fig. 5-A shows, XoSoft, during Control Strategy 2 trials, effectively increases right leg's PKF from 45±13.8° to 53±3.2°, decreasing the risk of tripping due to foot drop. Unfortunately, left hip shows major changes due to compensation movements of the subject ("whipping" movement) resulting in both higher left PHF and hyperextension in both Control Strategy 1, 2. This undesired effect could be resolved with a long training session of the subject. However, right PHF and RoM (Fig. 5-A and 5-F) are positively altered by XoSoft with Control Strategy 2, decreasing peak of 6° and median RoM of 14°. Even if Control Strategy 1 creates a right PKF of 70±3°, this effect is due to an excessive and undesired user's compensation movement against the rubber bands, which are always engaged.
In fact, Fig. 5-A shows a high peak in right PHF with Control Strategy 1. Results show that for all Control Strategies, the

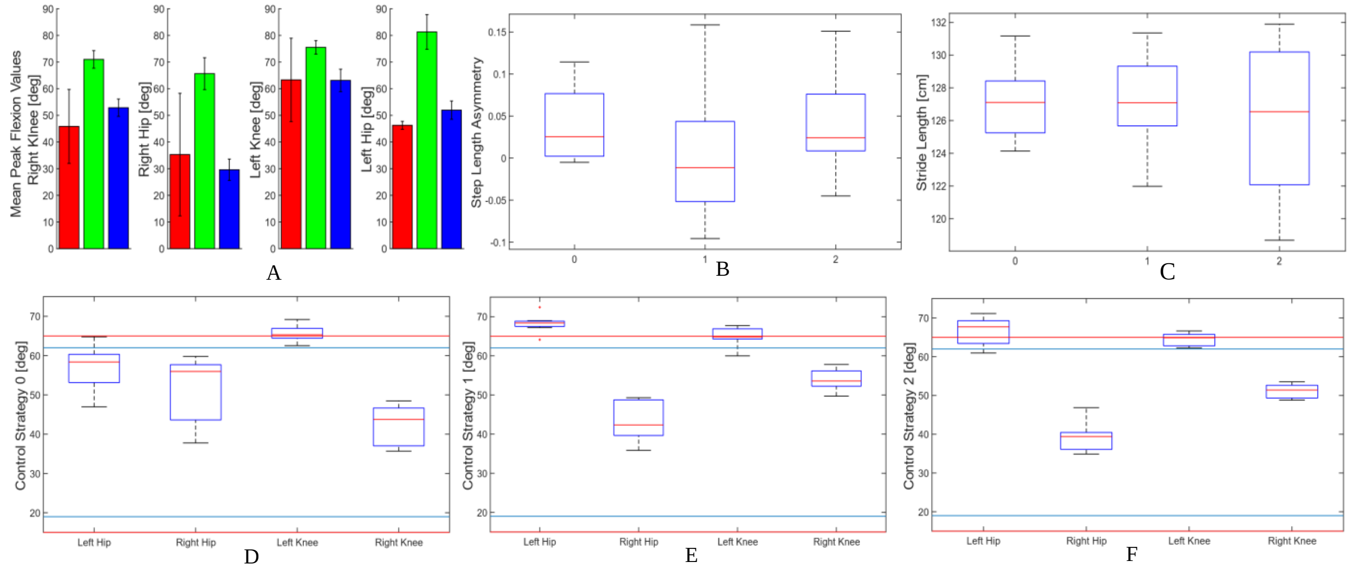

Figure 5 Charts of the evaluated indexes in Sagittal Plane. In (A) Red bar refers to all trials of Control Strategy 0, Green to Control Strategy 1 and Blue to Control Strategy 2. In (B), (C) plots 0,1,2 refer to different Control Strategies. In (D), (E), (F) blue horizontal lines show the maximum and minimum mean values for hip RoM, red for knee RoM from [9]

median values in joints RoMs and SLA are consistent with values for post stroke patient [9]. However, Stride length value resembles a healthy subject's one (132±1.3 cm) [9].
Both Stride and SLA show little differences (0.5% and 5%) with trials without XoSoft and Control Strategy 2. In addition, during the same trials, Control Strategy 2 was validated to save active work for the hip joint [8]. So, the XoSoft Beta-1 with an appropriate set of QPAs and a control strategy tailored for the subject, proved to be addressing the mobility problems affecting the user.

IV. Conclusions

In this work XoSoft Beta-1 prototype, a modular assistive exoskeleton designed for frail elderly, post stroke and partial SCI patients, is presented and its performances are assessed through analysis of a post stroke elderly male subject's gait data (Step Length Asymmetry, Range of Motion and Peak Knee and Hip Flexion angles). Data gathered during tests show that this prototype enhances key values that were altered by the subject's post-stroke condition. In fact, in Fig. 5-A and 5-F show a decrease of impaired hip hyperextension (from 36° to 30°) and improvement in maximum knee flexion angles to reduce foot drop tripping (from 45° to 53°). These results, in addition to the promising findings in [8] where the hip module is assessed to provide a net energy reduction of ~9% as the QPA's assistance measured as ratio between the exoskeleton's and biological power, show encouraging effects of the exoskeleton design and control strategy; proving that modularity of actuation works to address specific needs of the patient, decreasing hip muscle's work and lowering the risk of tripping due to foot drop. However, to improve these results, a more precise gait segmentation algorithm for better actuation timing is needed. Indeed, each QPA should be activated in different phases for specific gait problems without altering greatly any other gait parameters. The electromagnetic clutches need to be replaced with an equivalent soft mechanism to improve comfort and decrease the overall weight of the system (Table 2). In conclusion, new trials and different patients are needed to gather more data for statistical analysis. This would lead to a deeper understanding of the effects of XoSoft on the patient and how the subject reacts to the exoskeleton itself.

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