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SCRIPT Passive Orthosis: Design and Technical Evaluation of the Wrist and Hand Orthosis for Rehabilitation Training at Home

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***Abstract*—In this paper, a new hand and wrist exoskeleton design, the SCRIPT Passive Orthosis (SPO), for the rehabilitation after stroke is presented. The SPO is a wrist, hand, and finger orthosis that assists individuals after stroke that suffer from impairments caused by spasticity and abnormal synergies. These impairments are characterized in the wrist and hand by excessive involuntary flexion torques that make the hand unable to be used for many activities in daily life. The SPO can passively offset these undesired torques, but it cannot actively generate or control movements. The user needs to use voluntary muscle activation to perform movements and thus needs to have some residual muscle control to successfully use the SPO. The SPO offsets the excessive internal flexion by applying external extension torques to the joints of the wrist and fingers. The SPO physically interacts with the users using the forearm shell, the hand plate and the digit caps from the Saebo Flex, but is otherwise a completely novel design. It applies the external extension torques via passive leaf springs and elastic tension cords. The amount of this support can be adjusted to provide more or less offset force to wrist, finger, or thumb extension, manually. The SPO is equipped with sensors that can give a rough estimate of the joint rotations and applied torques, sufficient to make the orthosis interact with our interactive gaming environment. Integrated inertial and gyroscopic sensors provide limited information on the user's forearm posture. The first home-based patient experiences have already let to several issues being resolved, but have also made it clear that many improvement are still to be made.**

Keywords*—*exoskeleton, orthosis, hand, wrist, finger, thumb, rehabilitation, stroke, parallelogram mechanism, finger measurements.

I. INTRODUCTION

The hand is located at the distal end of the upper limb kinematic chain, where it functions as its end-effector. The hand is both an organ of information and an organ of execution [1]. Its very specialized anatomy and the large cortex area dedicated to the hand function (∼30%) reveal the essential role that plays in our lives [2].

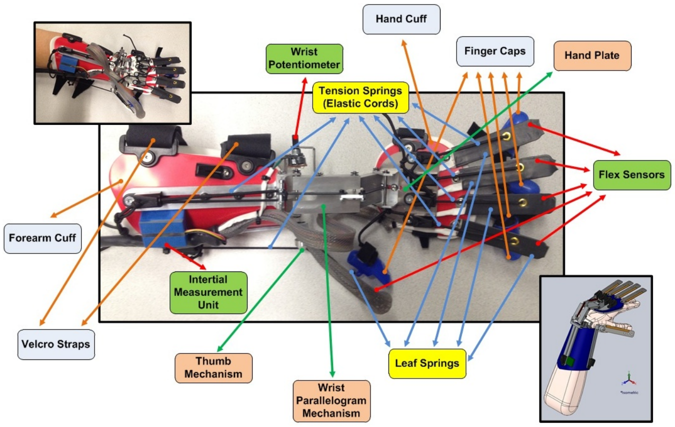

Fig. 1. The SPO with all its components

Stroke generally affects motor functions of the hemiparetic lower and upper limb. The main characteristics observed in hemiparetic patients are: weakness of specific muscles, abnormal muscle tone, abnormal postural adjustments, lack of mobility, incorrect timing of components within a pattern, abnormal movement synergies and loss of interjoint coordination, and loss of sensation [3]. These impairments are often linked together. The hand, because of its complexity in terms of muscles and joints to control, is likely to be impaired after a stroke and affected by the previously listed symptoms. Thus, it limits patient's autonomy in activities of daily living (ADL) and potentially results in permanent disabilities [4].

Recent developments such as SaeboFlex [5], HWARD [6], MIT-MANUS hand module [7] showed the potential and

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efficacy of robotic devices for rehabilitation of stroke patients [8]. From the state of the art of hand exoskeletons and their requirements [9] it is clear that the ideal orthosis for rehabilitation should be as much non-invasive, light weight, easy-to-use, mechanically transparent, and safe as possible. It should cover as much natural RoM as possible and not impede natural human movements while dealing with the technical challenges. These technical challenges can be listed as the many degrees of freedom (DoF's) with nonconventional joint structures and the center of rotation (CoR) alignment problem [10] of each individual link.

The SCRIPT Passive Orthosis (SPO) offers a complete solution dealing with all these technical challenges. The SPO is equipped with sensors that enable users to play interactive therapeutic video games. The sensor data is also used to monitor the progress of the patients by the physiotherapists.

The SPO is a new design with its sensorized architecture, wrist flexion/extension mechanism and finger flexion/extension mechanism. It is a part of the EU-FP7 Project SCRIPT (Supervised Care and Rehabilitation Involving Personal Telerobotics) that aims to investigate current challenges in hand and wrist rehabilitation orthoses which will be used by stroke patients at their homes [11], [12].

II. REQUIREMENTS

A. User Requirements

The basic structure of the human hand can be considered in terms of its bones, associated joints and muscles. Standard terminology used to refer to the various digits and parts of the hand is given in [9]. The hand has a dorsal surface, a volar or palmar surface, and radial and ulnar borders. There are 27 bones in the hand: 8 carpal bones constituting the wrist, 5 metacarpal bones in the palm, and 14 phalangeal bones that make up the digits (2 in the thumb and 3 in each finger) [13], [14]. After stroke, many individuals suffer from too much flexion in the hand. They are not able to relax the flexors or engage the extensors sufficiently to allow the hand to open. The primary requirement for the SPO is therefore to provide the user with additional extension forces that allow him to handle objects. These added extension forces shift the equilibrium point of the relaxed hand to a more open position.

The general user requirements for the SPO can be listed as covering the RoM's of an healthy hand/wrist as much as possible, providing a mechanical design which is not impeding the natural hand/wrist movements, ability to adjust initial tension forces manually, low weight, reasonable price, easiness to don/doff, and providing sensory feedback to the therapeutic video games.

The RoM values for the SPO are decided by the physiotherapists as shown in TABLE I [15], [16], [17].

III. DESIGN

In several iterations, the user requirements were transformed into a workable design and the accompanying technical specifications that are detailed in the following paragraphs.

TABLE I. RANGE OF MOTIONS REQUIREMENTS OF HAND/WRIST

Segment	Joint	Degree of Freedom	Max [deg]	Min [deg]
Forearm	Wrist	Flexion/Extension	40	40
Thumb	CMC	Palmar Abduction	50	0
	CMC	Radial Abduction	20	0
	MCP	Flexion/Extension	60	5
	IP	Flexion/Extension	80	0
Index, Middle, Ring, Pinky	MCP	Flexion/Extension	60	5
	PIP	Flexion/Extension	80	0
	DIP	Flexion/Extension	80	0

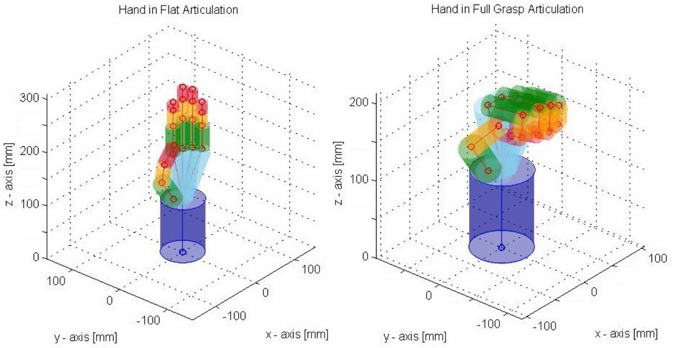

Fig. 2. Matlab model of hand and wrist articulations. This model was used to visualize the healthy and impaired hand movements and used as a basis for the 3D design of the SPO. Anthropometric data was taken from [18], [19] for this Matlab model.

A. Simulation Model of Human Hand and Wrist

A simulation model of mechanical properties of healthy and impaired wrist and hand was developed. Functional hand anatomy indicating all its bones and joints was used to derive this mathematical model of the hand and wrist. This model was based on a volumetric kinematic model. Wrist joint in this model was reduced as a fixed point in the carpal bones as well as metacarpal bones were assumed as fixed. They can move only around wrist joint. All the links, the joints, and the wrist joint assumption were defined in this volumetric kinematic model. Relative rotations were considered in the model. If a proximal link rotates, its middle and distal phalanx links also rotate.

This simulation model not only helps us decide the essential design guidelines, but also visualizes the RoM's for the healthy and impaired hand/wrist (see Fig. 2).

B. System Architecture

The SPO interacts with electronic and mechanical components such as sensors and springs. A separate forearm support helps users deal with the gravity. In the hardware (electronic) architecture, there is a dedicated microcontroller (low level) connecting to the analog sensors (bending (or flex) sensors and wrist potentiometer) to transmit the raw readings of these sensors to a dedicated PC (high level). This dedicated PC guides users to play therapeutic video games and to interact with physiotherapists and technicians. It is connected to a dedicated server and terminal computers of physiotherapist and technicians via TCP/IP protocol.

C. Physical Interfaces

The SPO physically interfaces with the forearm, hand and fingers of the users using respectively a forearm shell, a hand plate and individual digit caps (see Fig. 1). To guarantee safe and comfortable interaction, the SPO uses commercially available physical interfaces with a proven track record. They were acquired from Saebo Inc. (Charlotte, NC, USA). The Saebo forearm shells, hand plates and caps are available in multiple sizes and for both left and right hands that are needed to custom fit the SPO to a wide range of body dimensions. Two issues impeding natural human movements and limiting natural RoM should be mentioned. The digit cap blocks most of the DIP rotations, which assists users in making more useful finger movements. The hand plate prevents overextension of the MCP joint.

D. Finger Mechanism

The SPO applies the external extension torques on the fingers via passive leaf springs and elastic tension cords (see Fig. 4, 5). The leaf springs allow the extension force to be applied perpendicular to the fingertip for most of the range of motion, but cannot be directly attached to the finger due to misaligned digit axes of human and device. The leaf spring has cord guides through which the tension cord is routed and is covered in a shrink-wrap to protect the patients against its sharp edges. The tension cord is used to give the finger freedom of movement relative to the leaf springs. However finger abduction/adduction is not actuated, the finger mechanism does not block this DoF due to its structure thanks to elastic cords' flexibility. The cord is also used to adjust the amount of support by tensioning it more or less using the tension-cord stops on the top of the hand plate (see Fig. 1, 4).

E. Thumb Mechanism

The force generation and application mechanisms for the thumb are identical to the ones for the fingers. To allow additional freedom of movement in the thumb needed for thump opposition, the thumb mechanisms has an additional rotational degree of freedom that coincides with the wrist axis, with any misalignment being allowed for by the flexibility of the tension cords.

F. Wrist Mechanism

The wrist mechanism uses a double parallelogram between forearm shell and hand plate that allows wrist flexion and extension but blocks all other wrist rotations (see Fig. 3, 4). The double parallelogram is needed to prevent misalignment between human and device axes and make the device painless and comfortable to use. Through the parallelograms, the rotation of the hand around the wrist flexion-extension axis of the wrist is transferred to the parallelogram clamp at the forearm. There, this rotation is actuated using an elastic tension cord. The tension in the cord can be adjusted using the cord stops at the elbow end of the forearm shell.

G. Force Adjustability

The external extension force in the digits and the wrist can be adjusted by tensioning the elastic cords. The digits and the wrist have a single tension cords each, and each cord has multiple knots on it. These knots can be clamped in the cord stops on the device and tensioning the cord will produce more external extension force. The user is instructed to change the tension based on his impairment and his therapy progress via the physical therapist and the graphical user interface.

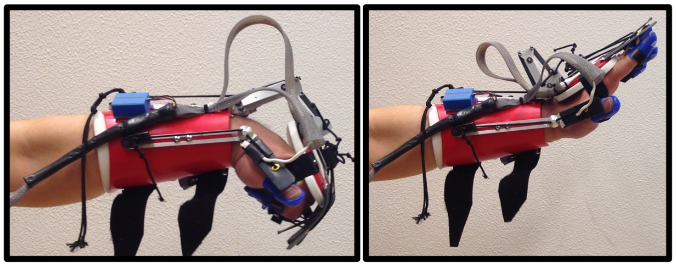

Fig. 3. The SPO allows user to do wrist flexion and extension movements.

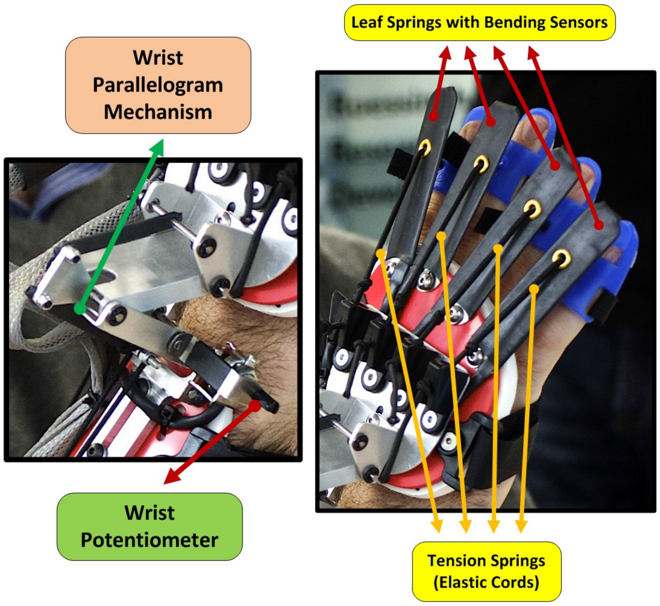

Fig. 4. Close-up view of the SPO wrist and finger mechanisms. Wrist flexion and extension movements are achieved with the help of a double parallelogram mechanism. This mechanism only allows wrist for flexion and extension movements. It also has a potentiometer to measure wrist flexion and extension. Finger mechanism consists of a combination of a leaf spring, an extension spring (elastic cord) and a bending sensor. Knots on the elastic cords allows user to manually adjust initial tension and total force value applied on the finger.

H. Aesthetic Properties

The SPO closely follows the contours of the human body. Most components stay within a volume less than 30 [mm] away from the body. The wrist parallelograms, needed to allow wrist flexion and extension, require approximately 75 [mm] from the body at maximum wrist extension. This distance can be seen in Fig. 3. The device is not overly disruptive when used as therapy tool, but it is too bulky to be a permanent aid for daily use.

To improve patient comfort, all sharp edges of the devices are either sanded down or covered using protective material such as plastic shrink wrappers. All electrical components (sensors and wirings) are covered using cable sleeves.

IV. SIGNAL PROCESSING

Sensor suite of the SPO has three different types of sensor which are bending sensors, potentiometer, and inertial measurement unit (IMU), respectively.

The bending sensors at the leaf springs and the potentiometer at the wrist mechanisms are sampled using the analog-digital converters in the Arduino Nano microprocessor board. The Arduino passes on the sampled values to the main computer system using an USB connection. The IMU [20] is connected to an serial-to-USB converter and again connected to the main computer system using a USB connection. For both, custom Windows 7 drivers were written to make the signals available to the graphical user interface and connected software.

The bending sensors are simply resistors varying according to bending angle. They are already used in off-the-shelf commercial products. They provide around 1 [deg] resolution with their highly affordable price (less than 8 USD for each sensor) [21]. They are connected to microcontroller (Arduino) with the help of divider resistors. To get the maximum resolution, the value of these divider resistors are optimized. The rotary potentiometer for the wrist is connected to microcontroller in the same way. Bending sensors are also used and validated in [22].

Total cost for sensor suite including microcontroller is cheap (less than 250 USD for each sensor suite) which satisfies one of the most important requirements with its acceptable performance.

A. Angle Estimation Algorithm

In order to extract MCP, PIP, and DIP rotations from a single measurement with the help of one bending sensor, an angle estimation algorithm is derived in (1), (2).

Each flex sensor provides one bending angle reading to each individual finger. In order to extract each digits angular position (MCP, PIP and DIP rotations) from one sensor reading, some assumptions have to be made. It is assumed that there is no dead zone with the flex sensors and rotation of each phalanx is linear and covers the full range of motion except the distal phalanx. Finger caps overlap distal phalanx and middle phalanx at the same time and limit the RoM of distal phalanx drastically. Abduction and adduction movements are neglected, as well. In addition, an initialization/calibration procedure is required to measure the maximum and minimum raw sensor values. Similar approach can be applied to thumb and wrist.

$$\theta_{joint}(k) = \theta_{joint_{max}} \cdot |BSensor_{norm}(k) - 1| \tag{1}$$

$$BSensor_{norm}(k) = \frac{BSensor(k) - BSensor_{min}}{BSensor_{max} - BSensor_{min}} \tag{2}$$

$BSensor(k)$ is the raw reading of the bending sensor of sample k. The indices max, min and norm indicate the respectively maximum, minimum and normalized values of $BSensor$. $BSensor_{min}$ is measured while all fingers are stretched on a flat surface such as a desk. $BSensor_{max}$ is measured while user performs a full grasp without any object. $\theta_{joint_{max}}$ refers to maximum rotation of joints in [degree]. $\theta_{joint}(k)$ refers to estimated rotation of joints in [degree]. In Equation (1), indice joint refers to a set of $\{MCP, PIP, DIP\}$. Equation (2) is used to normalize raw readings of bending sensors. These raw readings may vary due to various reasons such as sensor tolerances, divider resistor tolerances, different hand geometries, etc. The value of this scaling factor spans between 0 and 1. $BSensor(k)$ values have units in [LSB] which refer to "Least Significant Bit" in a range from 0 to 1023 with a 10-bit Analog-to-Digital Converter (ADC). $\theta_{joint_{max}}$ is the max rotation of each MCP, PIP and DIP joints. In our experiments, we recorded a video and used the frames of this video to determine $\theta_{joint_{max}}$ values. In Equation (1), $BSensor(k)$ values are used to extract MCP, PIP and DIP rotations by interpolation with the help of $\theta_{joint_{max}}$ values.

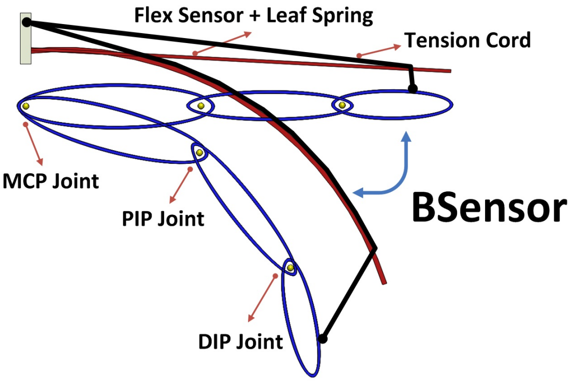

Fig. 5. Angle estimation diagram helps to estimate each joint's rotation with the help of one bending sensor. Bending sensors are placed on the leaf springs and follow the finger movement as shown in the diagram. The distance between the leaf spring and the finger varies according to the finger flexion. However it brings some nonlinearities, it allows to deal with the complexity of finger anatomy in a very efficient and simple way. Most of the DIP rotations is blocked by the digit caps.

B. Validation

Validation results are depicted in Fig. 6 and 7. The current performance of the sensors is tested with different therapeutic video games and found sufficient to play these therapeutic video games. These games cover all possible wrist and finger articulations that the SPO allow users to articulate such as wrist flexion/extension, finger flexion/extension. In order to improve the performance of angle estimation algorithm, assumptions should be improved.

Results based on the angle estimation algorithm for the middle finger can be seen in Fig. 6. These results are manually validated with the help of experiment video recording. Relevant frames from this video recording are used to validate the results. Measured maximum values of θ_{MCP}, θ_{PIP} and θ_{DIP} are 52 [deg], 90 [deg] and 6 [deg], respectively. Measured sampling frequency is around 60 [Hz] which is sufficient for real time applications.

A cylinderical mug with the diameter of 84 [mm] is grasped with the orthosis. Measured values of θ_{MCP}, θ_{PIP} and θ_{DIP} for this grasping experiment are 47 [deg], 26 [deg] and 4 [deg],

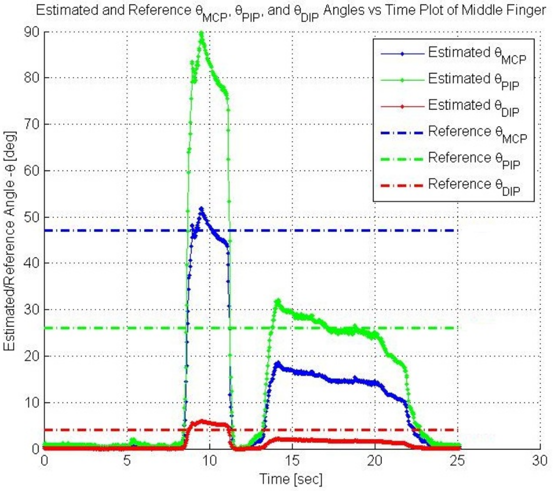

Fig. 6. An object grasping experiment results consist of three different phase. The first phase (0∼5 [sec]) holding hand flat and the second phase making a full grasp without any object (8∼12 [sec]) are for calibration of bending sensors. The third phase is object grasping phase (16∼19 [sec]). Estimation of MCP, PIP and DIP rotations is given in blue, in green, and in red, respectively. It can be seen that there is a lack of DIP rotation due to the fact that most of DIP rotations is blocked by the digit caps.

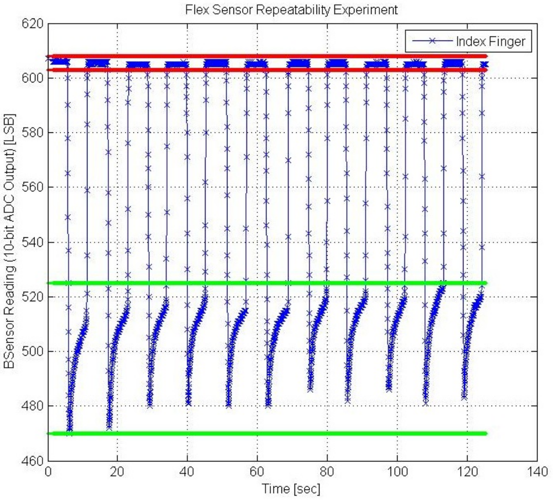

Fig. 7. An experiment for reproducibility is completed. From flat position of the fingers, several grasp articulations with a cylindrical object (40 [mm] diameter) were performed in order to see if bending sensors provide similar values. It can be seen that repeatability performance of the sensors is acceptable. But, the accuracy is poor and suffers from the natural decay in step response.

respectively. Estimation of θ_{MCP}, θ_{PIP} and θ_{DIP} can be seen in Fig. 6. In subsequent experiments, we were not able to distinguish between three cylinders with diameters 84 [mm], 60 [mm] and 50 [mm] based on the sensor readings, primarily due to the natural decay in step response in the chosen flex sensors that makes it hard to get accurate absolute values from the sensors.

V. DISCUSSION

Donning and doffing of the SPO do not require external help. Subjects handle with donning and doffing of the SPO by their healthy hand. It is already tested with healthy subjects. For healthy subjects, it takes around 5 [minutes] in total for donning and doffing. The clinical partners of the SCRIPT project have already started the real experiments with actual stroke patients at their places. So far, it was observed that some stroke patients are in need to use the SPO with external help. However, the SPO has an advantage compared to the SaeboFlex, because with the SPO, patients can move their wrist (and it is not fixed in extension) which makes it easier to don and doff the SPO. But the SPO still needs to be tested with the patients who have severe spasticity.

Subjects need to follow a well-defined procedure for donning and doffing, which includes, in shortly, donning forearm shell, hand cuff, finger caps and vice versa for doffing. Familiarity with the orthosis improves the donning/doffing process of the subjects.

Pronation/supination movements of the wrist is notably restricted. Adding pronation/supination DoF to the system makes the orthosis really complicated in terms of mechanical engineering and heavy since this joint is spread between wrist and elbow.

The SPO increases the users' independency. It is a functional and less complex hand and wrist orthosis. It is affordable for home use when compared with clinical expenses. It has a very light weight. Its weight is about 0.650 [kg] with cable harness and is about 0.400 [kg] without cable harness. It is also possible to use the SPO with the integration of forearm supports. In our tests, we used SaeboMAS forearm support without any structural modification.

The SPO is able to deal with misaligment problem of the joints with the help of its wrist and finger mechanisms.

We would like to emphasize the fact that since the SPO is a passive device, it does not pose critical danger to the users wellbeing. The SPO is a device with only springs and no actuators (electrical motors etc.) in any form, so it does not transfer external energy to the hand or wrist. This is an inherently safe device because the subject cannot be forced into a position (s)he cannot achieve by him/herself. All movement performed while wearing the device needs active movement by the person him/herself. Furthermore, it should be noted that the basis of the SPO is composed largely of the SaeboFlex components (forearm cuff, hand cuff and finger-end caps), and has in general comparable functions and mechanisms. These parts already comply with clinical safety requirements since they are currently being produced for Saebo (with CE mark), which have been in safe use for over 10 years across the US and Europe, in similar purposes as those pursued by us.

We also would like to say that the clinical partners of the project started to test the SPO with several patients. These training sessions will take 6 weeks at home. So far, two patients are about to finish their 5th week. In total more than 10 patients will test the SPO for evaluation of the SPO. The recommended training sessions include 180 minutes training per week at home for 6 weeks by the clinicians.

So far, we have identified some failures with the SPO. Extension springs (elastic cords) for the wrist are damaged due to intensive use. We provide spare elastic cords in case of failure for immediate change without any use of specific tools. In addition, while grasping hand cuff is not perfectly fixed. It may lead some misreadings in finger sensors and exerting less extension forces. Another solution to fix this problem should be suggested such as using additional and diagonal Velcro straps instead of one. We also noticed that the force/torque provided by the wrist orthosis should be improved. We plan to increase the stiffness of this elastic cord.

IMU perfomance improvements are still in progress. It has an acceptable performance to identify the required gestures such as wrist pronation/supination, moving forearm to the backward/forward. It sometimes fails to identify these gestures. Software improvements are needed and in progress at this moment.

The real stroke patients reported that the SPO motivates them to use it at home with the therapeutic video games which is one of the main objectives of the SPO use.

VI. CONCLUSION

In summary, design, technical evaluation and validation of the SPO which are fulfilling the user requirements are completed. However it resembles with SaeboFlex at the first glance since we use same SaeboFlex interface parts such as forearm shell, hand cuff and finger caps, we completely redesigned it to make it useful for rehabilitation at home and interfacing with gaming, support, and therapeutic software modules. Instead of fixed rigid metal bars guiding fingers' cords, we used leaf springs which are able to nicely follow the natural finger movements. With the help of these leaf springs, we are able to place bending sensors providing the finger flexions and to keep extension force vectors as perpendicular as possible in an essential RoM of fingers. In addition, since the SPO allows the users to move their wrist in flexion/extension, elastic cords make the SPO easy to don/doff. Thus, it makes the SPO completely different from the SaeboFlex.

An angle estimation algorithm in order to extract MCP, DIP and PIP rotations from one single measurement (total finger flexion) is derived. Due to the decaying step response, the sensors are able to provide us with relative (movement) values only, which should be sufficient for movement sensing, but hinders absolute progress recording. These issues should be resolved in the next version of the SPO.

As future works, there will be improvements of the SPO and active-version of it. We plan to replace elastic cords with the actively actuated wires. Thus, we will be able to adjust the stiffness of these cords online in order to exert any extension force/torque required by the patients who suffer from different level of stroke.

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