DYNASUIT, INTELLIGENT SPACE COUNTERMEASURE SUIT CONCEPT BASED ON NEW ARTIFICIAL MUSCLES TECHNOLOGIES AND BIOFEEDBACK

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ABSTRACT

The purpose of the DYNASUIT project is to design a new intravehicular body suit for countermeasure purposes, including state of the art technologies in artificial muscles, body monitoring and biofeedback.
This paper presents the outputs of the first phase of this on-going activity. First, the weightlessness effects of microgravity on the body and the current countermeasure solutions are described. The main potential scenarios for DYNASUIT are then described, followed by details of the preliminary concepts and associated technologies for bio-monitoring and artificial muscles.

1. INTRODUCTION

During spaceflight, the human body is subject to physiological adaptation to the microgravity conditions. Although some effects, like vestibular disorders, only lead to temporary discomfort for some days, other reactions such as bone mineral loss or muscle atrophy impact the physical condition of astronauts in proportion to the time spent in space. This is an issue for long-duration missions such as those onboard the ISS and for future planetary exploration on the Moon and Mars.

Health and fitness procedures and programs are required to mitigate the effects of living in microgravity, and ideally retain Earth-bound baselines. These approaches and related devices are collectively called countermeasures. For more than 50 years, countermeasure solutions have been developed and evaluated during spaceflight, including physical exercise apparatus, medication, nutritional supplementation, compression/loading clothing and artificial gravity concepts. The lack of efficiency of current countermeasure solutions and the longer exposure to microgravity for new missions require a more thorough understanding of the stakes and issues and the development of new solutions.

In this context, the purpose of the DYNASUIT project is to design a new intravehicular body suit for countermeasures purposes, and assess how the new available technologies in artificial muscles, body monitoring sensors and biofeedback could be valuable for this application. An intelligent suit containing biofeedback capabilities and the ability to accommodate different sensing, reporting and countermeasure subsystems (e.g. an intelligent muscle constraint system or a medical warning system) would allow astronauts to better support operational activities through counteracting the effects of weightlessness. As a replacement of normal intravehicular garment, it would be worn by the crew member during daily activities, providing a constant stimulus to bone/muscle. It could also be used in parallel to other existing countermeasure to improve their efficiency. Furthermore, an intelligent garment of this nature would offer another tool to scientifically evaluate the effects of the systems on crew health in the microgravity environment.

After a survey and analysis of known weightlessness effects of microgravity on the body and the existing countermeasure solutions, this paper describes the principal uses and scenarios foreseen for the countermeasure suit and presents the preliminary concept and technology candidates highlighted during the first phase of the activity.

2. PHYSIOLOGICAL EFFECTS OF WEIGHTLESSNESS ON THE BODY

The human body is capable of adaptation to environmental changes. This capability to adapt is such that the physical structure and function of many of the body's tissues, organs and systems alter to enable life to proceed in microgravity in an efficient and economical manner. The primary systems affected are the skeletal, muscular, neurovestibular, cardiovascular, endocrine, immune and motor control systems. Adaptations occur in hours to days for some systems but can take weeks to months or even longer for others. For example the neurovestibular system will typically adapt over 3 days with symptoms ceasing by day 5 for most people, whereas the musculoskeletal system will adapt continuously for months depending on the stimulation experienced, with bone potentially still deconditioning after a year or more.

These changes, seen over hours, days, weeks and months, are a positive response to the space environment, in particular to the absence of gravity. However, they are problematic if the gravity vector is re-imposed, when coming back to Earth, during planetary excursions (increasing the risk of injury), or when Earth related achievement standards are necessary in-flight e.g. during emergencies. These are typical events that must be planned for in exploration missions. The following sections present the principal kinds of deconditioning that are considered during this activity and could be potentially managed by a countermeasure suit.

2.1. Bone Atrophy

The skeletal system is weakened through the demineralisation and atrophy of bones, primarily in the bones that are normally weight bearing on earth e.g. the pelvis, femur and lower vertebrae. Although this phenomenon is not completely understood, it is relatively clear that the balance of turnover of bone is detrimentally altered in the absence of the static loading present in 1-g, and by reductions in the dynamic loading applied by impact and muscle activation.

Without countermeasures, load bearing bones can lose 1 to 2% of their density per month for extended periods leading to clinically relevant conditions in one or two years or even less. Moreover, losses still occur in spite of the crewmembers' participation in exercise [1]. Bone atrophy is considered to be the most serious physiological consequence of body deconditioning in the microgravity environment due to the continuous nature of the deconditioning, the risks of fracture and the time required for post-mission convalescence [2].

2.2. Muscle Atrophy

In the absence of adequate countermeasures, microgravity causes muscles to atrophy and alters muscle morphology, with a resulting loss of contractile mass and performance capability. This loss reduces the speed and strength of muscular contraction and thus the power capabilities. Most of the muscle losses occur in the lower limbs. For limited periods, strength reductions may be in the region of 2 to 5% per week depending on the site and function of the muscle [3]. Soleus peak power for example has been reported to be 32% lower after 6 months on ISS, even with modern exercise countermeasures in place [4].

2.3. Body Elongation

The lack of normal loading during spaceflight causes astronauts to spine elongation of up to 70mm, with significant back pain reported by approximately 50% of US crewmembers [5]. Furthermore, this elongation complicates the precise fitment of EVA spacesuits and can impact crew mission performance through poor quality sleep for those suffering discomfort.

2.4. Cardiovascular Deconditioning

The cardiovascular system deconditions due to reductions in metabolic enzyme levels, the size and quality of capillary beds and energy producing organelles. The main effects observed when returning to gravity conditions are decreases in maximal aerobic capacity, increased heart rate for any given level of exertion and orthostatic intolerance. Currently, 80% of astronauts returning from ISS experience greater than 6% loss of maximum oxygen uptake despite a rigorous countermeasure programme.

Orthostatic intolerance, the inability to maintain the standing position under +1Gz, is a consequence of cardiovascular deconditioning. Due to the risk of syncope (fainting), it is a major problem specifically during re-entry in the atmosphere. The incidence of orthostatic intolerance varies according to space mission duration and the effectiveness of countermeasures, but has been seen to be greater than 90% after some long duration missions [6].

2.5. Neurovestibular and Sensorimotor Deconditioning

The neurovestibular/sensorimotor systems are acutely affected by the loss of the gravity vector resulting in physical space sickness, disorientation and a deconditioning of the proprioception system and associated structures. Upon return to Earth, astronauts must readjust to gravity and can experience problems standing up, stabilizing their gaze, walking and turning, and retaining posture. The magnitude of sensorimotor disturbances after gravity transitions increases with the duration of microgravity exposure, which is of particular relevance to long duration spaceflight. Such disturbances may impact operational activities including approach and landing, docking, remote manipulation, extravehicular activity and egress (both normal and emergency), and thus compromise crew safety, performance and mission success. It is believed that this sensorimotor deconditioning results from in-flight adaptive changes in central nervous system processing of information from the visual, vestibular, and proprioceptive systems [7].

3. EXISTING COUNTERMEASURES SOLUTIONS

3.1. Stimulation Requirements

Skeletal deconditioning is due to the reduction or absence of loading in the microgravity environment. Loading bone invokes slight deformations, or strain. On earth, the mechanical loads that cause skeletal strains are applied via weight bearing stress, and during muscular contractions e.g. when walking/running. To maintain bone health, it is theorized that both of these regimes need to be duplicated during microgravity exposure [8]. Normal long-axis static loading may also inhibit vertebral disc expansion and connective tissue strain, and preserve lumbar lordosis and normal spinal curvature [9]. The exact manner (magnitude of force, frequency, duration) in which this gravity loading should be applied for optimal stimulation is still under investigation, but work conducted by Cavanagh and Rice [10] highlights the need to provide a daily loading stimulus which equates to that experienced on Earth.

On the other hand, some authors see potential benefit in the use of vibration to stimulate bone [11]. They demonstrated that brief periods (<20 minutes) of a low-level (0.2g, 30 Hz) vibration applied during quiet standing can effectively inhibit bone loss in the spine and femur [12].

With respect to skeletal muscle, it must be highlighted that two forms exist, mobilisers, which are the large predominantly peripheral muscles used for movement, and stabiliser muscles, often found deep within the body, which are used for stability, especially when counteracting gravity.

Stabiliser muscles are most effectively trained by sustained low level (<30% Maximum Voluntary Contraction) muscle activity. This involves no more resistance than the weight of the limb being moved [13]. "Sets" of 10 holds of 10 seconds, each, 3 times per day, and daily, are frequently suggested as being effective.

The optimal stimulus for the maintenance or growth of skeletal mobiliser muscles is high intensity muscular contraction, where the ratio of eccentric to concentric contraction is at least 0.8:1.0. Several sets (between 2 and 4) of high intensity contractions are required. The intensity is dictated by the resistance offered by the machine and typically should be sufficient to lead to muscle failure i.e. the inability to move against the resistance, after 6 to 12 repetitions.

For cardiovascular deconditioning, the typical prescription is a set of 3 fitness sessions of 20 to 40 minutes duration at intensity in the region of 60 to 80% of maximum heart rate. Such regimens attenuate the cardiovascular deconditioning normally observed, and may decrease the associated effects as orthostatic intolerance by means of reduced loss of or maintenance of blood volume [14]. Furthermore, the stimulus presented to the muscles by the repeated muscular contraction acts positively on protein turnover so as to reduce the rate of space flight induced muscle atrophy. Another benefit is the repeated application of force loads along the long axis of the anti-gravity bones, which lows microgravity induced bone demineralisation and atrophy [15].

Mechanical stimulus on the soles of the feet may provide proprioceptive stimulation and reduce sensorimotor deconditioning. Layne et al (1998) [16] noted that "foot pressure may be useful for facilitating neuromuscular activation throughout the course of a space flight, thereby perhaps attenuating muscle atrophy and the associated post-flight motor control deficits experienced by crewmembers". It is of interest to note that the vast majority of astronauts on return from space exhibit an inefficient and at times problematic gait for some days, clearly indicating that current countermeasures do not prevent motor control deconditioning.

3.2. Methods and Devices

For long-duration missions on-board the ISS, astronauts are allowed for 2.5 hours per day for exercise training, with about an hour of this time spent for setup and post-exercise personal hygiene. Exercise time is typically split into two periods with one session for cardiovascular activities and another for resistance exercise. Different kinds of devices are (or have been) installed onboard the ISS.

Treadmills (e.g. TVIS, T2-Colbert) allow the user to undertake aerobic exercise involving the major +1Gz locomotive muscles during running/walking. For the exercise to be effective the user must be pulled down onto the track surface with a load that is a significant fraction of that experienced on Earth (e.g. elasticised bungee system providing 60% of terrestrial body weight load).

Cycle ergometers (e.g. CEVIS) are mainly used for aerobic exercise and muscular endurance with more comfort than with treadmills. They lack however +Gz and vertical impact stimulation. These devices also offer ways to the upper body e.g. through arm cranking

exercises.
High resistance devices, like the IRED or the ARED enable the crew to perform most major resistance exercises able to be conducted on Earth with a stimulation profile corresponding to that seen on Earth. Elasticized bands and expander spring systems are also used from time to time; however, the force/velocity relationships are not the same as Earth bound devices and are thus suboptimal. These can simply act in support of primary systems such as ARED.

Despite extensive in-flight exercise, most astronauts experience difficulties in standing, walking and orientation for several days after landing. This shows that the current countermeasure programs are limited in their ability to deliver the required results. But, beyond this, there are other limitations of the current countermeasure devices:

- They present a large footprint in the station in terms of volume, mass and power usage.
- Significant maintenance time is required. Currently all key exercise devices on ISS are encountering regular breakdowns.
- Added systems, like vibration isolation platforms or limitations on use, are required to prevent dangerous resonance occurring in the ISS structure.
- Each device affects typically one (or maximum two) physiological system.
- They are designed for generic use and are not individually tailored.
- Are not appropriated for long-term daily use.
- They can involve some pain discomfort (e.g. treadmill harness system)

Beside exercise devices, other tools have been considered for countermeasure purposes. The Russian Pingvin Suit is a muscle and bone loading countermeasure suit for use in microgravity that was designed to induce weight-bearing stresses on the skeleton and resistive exercise to the musculature [17]. As shown in Figure 1, bungees cords above and below a leather waist-belt create permanent compression along the z-axis for skeletal stimulation and offer resistance to postural muscle action. The upper body can be loaded up to 40kg. In-flight, the suit is supposed to be used during daily activity and in conjunction with countermeasures such as cycle ergometers. The un-calibrated bungee straps are adjusted individually for comfort. Despite its low weight (3.8kg), cosmonauts have found the suit to be hot, and the 1 or 2 stage loading system to be uncomfortable. One of the key reasons for crew not wishing to wear the Pingvin suit is hygiene, because the suits are not washable and therefore smell after some period of use in-flight.

Figure 1: Pinqvin-3 on ISS Expedition 4 (left (Photo: NASA ISS004-E-9194)) and bungee structure (right)

Another design, the Gravity Loading Countermeasure Skinsuit (GLCS) is an in-flight countermeasure suit under development that aims to apply loading to the body to mimic standing or daily static loading dosages [18]. The aim is for it to be integrated with other countermeasures to provide similar loads to those experienced when exercising on Earth. Compared to the 2-stage loading Russian Penguin Suit, the elastic mesh of the current GLCS prototype creates a loading regime that gradually increases in hundreds of stages from the shoulders to the feet. This reproduces the weight-bearing regime normally imparted in a +1Gz environment with much higher resolution and comfort.

Finally, other methods like electro-stimulation or pharmacological intervention can be implemented in parallel to the above exercises to augment the main device effects.

4. DYNASUIT SCENARIOS

As a countermeasure device, the primary application of the DYNASUIT will be, to improve crew health by reducing muscle/bone and motor control deconditioning presently encountered during long duration space flight. Two main potential scenarios have been highlighted for an active intelligent suit based on a bio-feedback loop control and including bio-sensors and actuators.

4.1. D-DYNASUIT for Daily Activities

As a replacement of the normal intravehicular garment (typically shorts/trousers and T-shirt or polo), the suit may be worn by the crew member during daily activities. It would help maintain an Earth-like gravity stimulus to the physiological system by providing low to medium levels of resistance or +Gz loading while a crew member conducts scheduled work tasks. As a consequence a countermeasure effect is provided during times which at present offer little possibility of physiological stimulus. The following characteristics are considered in the design of the D-DYNASUIT:

- Resistance to lower limb muscular contraction and motion (mostly affected by

deconditioning), by simulating limb weight profile as in a 1-G environment (purpose: stimulation of weight bearing bones and stabilizer muscles)
- Resistance/stimulation of trunk stabilizer muscles (purpose: mitigation of spine elongation and back pain, stabilizer muscles atrophy)
- Continuous long axis, graded, static +Gz loading profile, similar to that felt on Earth with potential added vibration periods (purpose: prevention of muscles and bone atrophy).
- Foot sole stimulation by the provisions of pressure patterns (purpose: limitation of the neuro/sensori-motor deconditioning).

4.2. E-DYNASUIT for Exercises

The E-DYNASUIT could be used in conjunction with existing countermeasures (e.g., while running on a treadmill or cycling) with a low to medium resistance, as well as act as a stand-alone device providing resistance to various motions to stimulate the skeletal and muscular systems with a medium to high resistance. E-DYNASUIT would provide variable resistance to motion around key joints with force levels typically greater than the forces foreseen for daily activities and would ensure both concentric and eccentric contractions. The E-DYNASUIT would enable the crew member to target identified in-flight and predicted deficiencies, mainly for mobilizer muscles, for instance after physical decrements have been highlighted via fitness evaluation (evaluations potentially obtained with the suit itself). The E-DYNASUIT could also be an effective way to load the body with graded +Gz loads or long axis vibration and impulse that could help provide additional stimulus when used in conjunction with other countermeasures such as the A-RED, CEVIS or TVIS.

4.3. Scenario Discussions and Benefits

When analyzing the potential scenarios, different designs can be envisaged. To focus such considerations, the D-DYNASUIT has been selected as the main scenario. With respect to the E-DYNASUIT as a stand-alone exercise device, preliminary analysis suggests that it may require forces/torques of a magnitude not compatible with the foreseen artificial muscle technologies (see after) and constraints like size, volume and suit integration.

Through an analysis of the currently available countermeasure solutions and their corresponding limitations and by anticipating the potential applications, the principal benefits derived from the use of the D-DYNASUIT concept countermeasure suit are like to be:

- Crew time savings, due to 1: the continuous daily stimulation and a potential reduction in the need for specific exercises and 2: maintenance time (compared to current primary devices).
- Lower footprint in terms of volume, power and mass, compared to current key devices.
- Real-time feedback, to crew, medical operation teams and scientist via biosensors information.
- More effective targeted and flexible countermeasure programs, with stimulation variation possibilities due to the active nature of the artificial muscles and their associated controllers and biofeedback loops.
- Simpler maintenance and better reliability with the added value that a suit can be more easily replaced than a big stand-alone device.

5. PRELIMINARY CONCEPTS AND TECHNOLOGIES

Figure 2 depicts the global architecture of the DYNASUIT system. It can be divided into several subsystems, each responsible for a specific task. For each subsystem, a trade-off analysis of the potential technologies is on-going based on specific technical criteria and other factors related to its application, for instance the compacity, suit integration, power consumption, comfort, usuability and safety.

5.1. Body Area Network (BAN)

This subsystem represents the network of bio-parameter sensors integrated in the suit, enabling the measurment of the physiological parametres of the user needed for the control and application of the suit. Typical measurments foreseen are the body position, EMG muscle signals, heart rate, electrocardiogram, body temperature, ventilation rate, blood pressure and oxygen saturation. For these last signals, the use of an integrated system like the LTMS-3 device [19] is envisaged.

5.2. Central Control Unit (CCU)

This subsystem is the brain of the suit. Based on the suit sensor readings, it manages the suit behaviour, including the biofeedback loops, the monitoring, the internal and external communications and the safety issues.

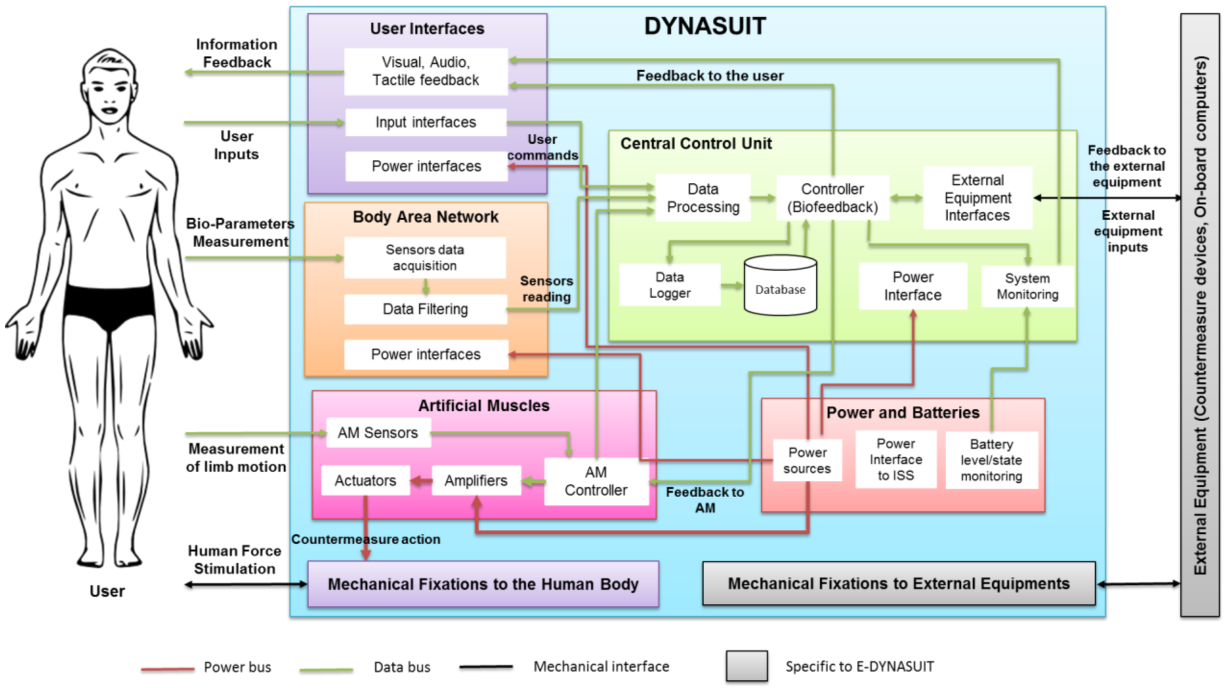

Figure 2: DYNASUIT subsystem overview

Biofeedback is the process by which physiological function of the user is reported and quantified with the aim of controlling the function in question. The feedback action can either be presented to the user or to support the equipment itself. In the first case, information is presented either by visual, audio or haptic means, or a combination of all, to induce a reaction or an adaptation of the subject behaviour (such as is seen with heart rate watches with alarm thresholds when running). In the other case, the feedback is used to control, in an autonomous fashion, devices and tools used by the subject (e.g. altered speed of a cardio device or adaptation of the artificial muscles behaviour). These two kinds of feedback loops will be integrated in the suit.

Based on preliminary analysis taking into account the requirements of the suit and criteria such as the processing power, it is proposed to make use of a distributed intelligent network, with a central processing unit, based on ARM like microcontroller and delocalized controllers for the actuators and sensors nodes, linked by data and power buses. This offers an easy way to add new components to the suit. The communication between the sub-systems is still an open question as the compatibility of wireless approaches, with the ISS environment has still to be evaluated. This will have an influence on the choice of the power distribution, with the possibility of a complete decentralized approach.

5.3. Artificial Muscles

The Artificial Muscles subsystem provides countermeasure actions by applying forces to the user body. It receives commands from the CCU, in the scope of the biofeedback control. Currently, two main technologies are in favour for integration in the suit: Electro-Active Polymers (EAP) and pneumatic.

The basic unit of dielectric EAP actuators consists of a dielectric elastomer film (e.g. silicone, acrylic elastomer) sandwiched between two compliant electrodes. When a voltage is applied between the electrodes, an electrostatic field in the dielectric occurs from the charges on the electrodes leading to an elastic elongation in the plane parallel to the electrodes and a contraction out of plane. By arranging several actuator layers in parallel, the resulting force can be multiplied and the stiffness of the created material can be increased. When the actuators are combined in series, the arising displacement becomes larger. Examples of applications for dielectric elastomers include mobile robotics, air vehicles and prosthetic devices [20]. Compared to other smart actuator families, the major advantages of dielectric EAP for this applications are the possibility to conform them in different shapes (planar, stack, …) facilitating their integration in a suit, their stress/strain behaviour and their efficiency. Figure 3 illustrates examples of EAP actuators.

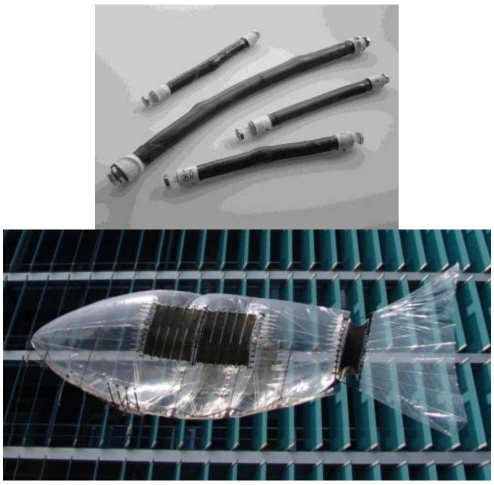

Figure 3: Examples of EAP actuators (stack and planar configuration)

Pneumatic actuators use a compressible gas, in most cases air, for energy transmission. The main benefits are their high payload to weight ratio and their natural compliance, important for safety aspects in human-machine interactions. The two different concepts of pneumatic technology to be used in DYNASUIT are the sigma actuator and the Tensairity actuator. For the sigma technology, compressed air is used to generate a tension force. It is a good candidate to offer variable axial gravity loading along the suit. The Tensairity actuator is a new concept that combines an inflated, flexible tube with cables and flexible struts [21]. Upon inflation, the inflated tube stabilizes the cables and the struts leading to an increase of the stiffness and straightening of the structure. It could be implemented for instance around the knee with a possibility to resist lower limb motion.

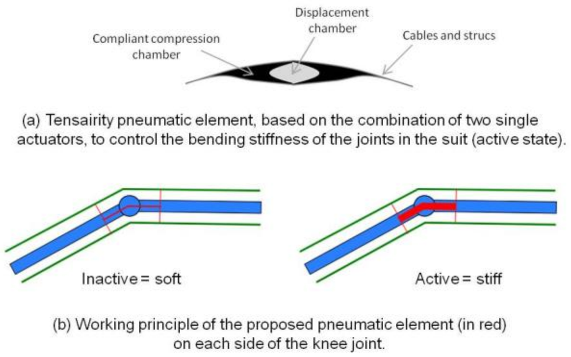

Figure 4: Tensairity pneumatic concept around the knee

Depending on the scenario and the nature of the required stimulation, the implementation and the layout of the artificial muscles can vary significantly. In some case, one of the two considered technologies offer better characteristics (e.g. foot sole stimulation for EAP, +Gz for pneumatic), but the conjunction of the two can also be envisaged, as for the trunk flexion that requires higher forces and bandwidth.

5.4. User Interfaces

These are the physical devices used by the astronaut to interact with the suit either recording user input commands or generating stimuli through visual, audio or tactile haptic displays. The main purpose of the user interfaces will be to allow the wearer to control the parameters of the bio-feedback loop and provide important information about the status of the suit or relevant physiological measurements.

6. CONCLUSIONS

This article presents the on-going DYNASUIT activity, aimed at designing a new intravehicular body suit for countermeasure purposes. It documents how the state of the art technologies in artificial muscles, physiological body monitoring sensors and biofeedback loops can be valuable in this application. After a review of the physiological effects of weightlessness and the current countermeasure methods and devices, the preliminary architecture and the first concepts for the principal suit subsystems have been described.

Ensuing activity will focus on the detailed design of the artificial muscle subsystem for one or two layout/technologies. This will be associated with the building of actuator test bench demonstrators that will enable the characterization and validation of the proposed actuators to be undertaken.

In parallel a dynamic simulation framework is currently under development to support, during this activity, the design of the actuator layout in the suit. In a later phase, this software tool could be extended to serve in support of the definition of the countermeasure exercises and strategies, as well as the definition and optimization of the bio-feedback control strategies.

The current project focuses on countermeasure scenarios, however, in the future, these technologies could find other space applications for example for the physiological/medical monitoring of astronauts, for additional training and simulation for extravehicular activities (under 0G or partial gravity) and as an in-flight or post-flight rehabilitation device with the aim of enhancing astronaut autonomy and self-reliance. Finally, outputs of this project could offer valuable terrestrial applications in the context of rehabilitation devices and body monitoring for human activities in extreme environments (e.g. telemedicine).

7. ACKNOWLEDGMENT

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