Designing a Soft-Actuated Smart Garment for Postural Control and Fall Prevention in Elderly Women

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Abstract. A fall in third age triggers a domino effect of consequences that are recognized by specialists as leading causes of further falls. After the first event, the post-fall syndrome onsets: a pathological fear of falling that affects quality of life. It leads to loss of self-efficacy, sedentarism, musculoskeletal weakening, reduced mobility, postural insufficiency, gait disorders, isolation and depression—all acknowledged as fall risk factors. Specialists agreed that the most effective approach to prevent new episodes is to restore confident postures and good alignments. This paper presents the first design stages of a soft-actuated re-educational garment for remote post-fall rehabilitation in female users. The objective is to i) restore postural control by providing a gentle pressure stimulus, suggesting corrections when poor body alignments are detected; ii) restore the perceived self-efficacy; iii) promote physical activity by motion monitoring and providing daily reports through a patient-therapist smartphone app. To date, we have tested a soft body-postures detection system by cross-checking data from a network of e-textile stretch sensors, along with a pneumatic actuator system around the user's torso providing a targeted pressure stimulus to correct bad habits. Tests have been run on a limited number of users due to the Covid-19 emergency. Data are not yet statistically conclusive but suggest the way to a new dimensional approach, both for rehabilitation and prevention.

Keywords: Smart clothing · Remote rehabilitation · Post-fall syndrome

1 Introduction

One of the main causes of falling among seniors is having already fallen [1]. A fall in third age triggers physical, psychological, and social decline, which is most of the time irreversible [2]. After the first event, a disabling syndrome onsets. They call it the post-fall syndrome [3]. The elderly develop a pathological fear of falling again whose primary symptom is a progressive postural insufficiency [4, 5]. It, in turn, triggers a domino effect of consequences: loss of self-efficacy, sedentarism, weakening of musculoskeletal system, reduced mobility, isolation, and depression—all consistent risk factors for further falls [3]. This is why researchers and specialists agree that, when dealing with fear,

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cognitive-behavioral interventions are highly advisable [6]. To date, the design science does not seem to have devoted much interest toward this disabling syndrome. Therefore, the question arises: is there a technology, or a combination of them, that might mitigate, and perhaps reverse, this functional decline? Systems for fall detection and prevention have been under examination for decades [7, 8]. Scientific research engines, such as Google Scholar or PubMed, provide a considerable amount of studies. However, by limiting the search to wearables, we can notice that little attention has been paid on smart garments as possible resources to develop and invest in. This study tries to somewhat remedy this shortcoming.

Designing a smart garment that ‘senses’ and anticipates the precise moment when the risk of falling may cause an injury is a challenge. Instead, to clothe seniors with something that might re-educate them and raise their awareness to the risk, stimulating their intrinsic abilities and perceived self-efficacy [9] is a goal that specialists recognize as worthy and valuable for practical verification. They agree that the most effective approach to prevent new episodes is to reinstate safe and confident posture and proper body alignment: regaining postural control is the essential condition for physical and psychological recovery. The end point of the patient’s journey, regardless of the outcome of the first fall episode, is always a postural and gait retraining that prevents recurrences [10]. This research aims to design a soft-actuated re-educational garment for post-fall rehabilitation in female users—in every cultural and geographic context, women are the most affected individuals [11]: they outnumber men by 40–60% in terms of injury rate, and by 81% in terms of hospitalization rate [12]. This wearable system has the objective to i) restore postural control, muscular strength and balance, by providing a gentle pressure stimulus, suggesting corrections when poor body alignments are detected; ii) restore the perceived self-efficacy relying on the ‘enclothed cognition’ factor, according to which the design and functions of the garment influence the wearers’ psychological and decision-making processes [13]; iii) promote physical activity by motion monitoring and providing daily reports through a patient-therapist smartphone application.

To date, we have tested a soft body-postures detection system by cross-checking data from a network of e-textile stretch sensors, along with a pneumatic actuator system around the user’s torso (qualitative test) conceived to provide targeted pressure stimuli. The first version of the garment is a full-body suit (shirt, waistband, and pant-legs) designed to smoothly integrate these technologies into three fabric layers: second skin, e-textile, and outer layer. The soft actuation and posture detection would be driven by the fourth (intelligent) layer: a soft lumbar device that, besides housing electronics and mechanics, serves as a cushion to maintain correct posture while sitting (see Fig. 1). This device will collect and process data and will be connected to a patient-therapist smartphone application—not detailed in this paper.

2 Method

2.1 Soft Posture Detection

To detect body posture and alignment, we selected the technology that best fits fabrics without stiffness and bulges and with the least impact on manufacturing processes [14]: the *Machine-stitched E-textile Stretch Sensor* a conductive thread weaved onto stretchable fabric using the *bottom cover-stitch* technique. This is a loop pattern whose elongation leads to a drop in the electrical resistance measured at the sensor ends (see Fig. 2 and its caption).

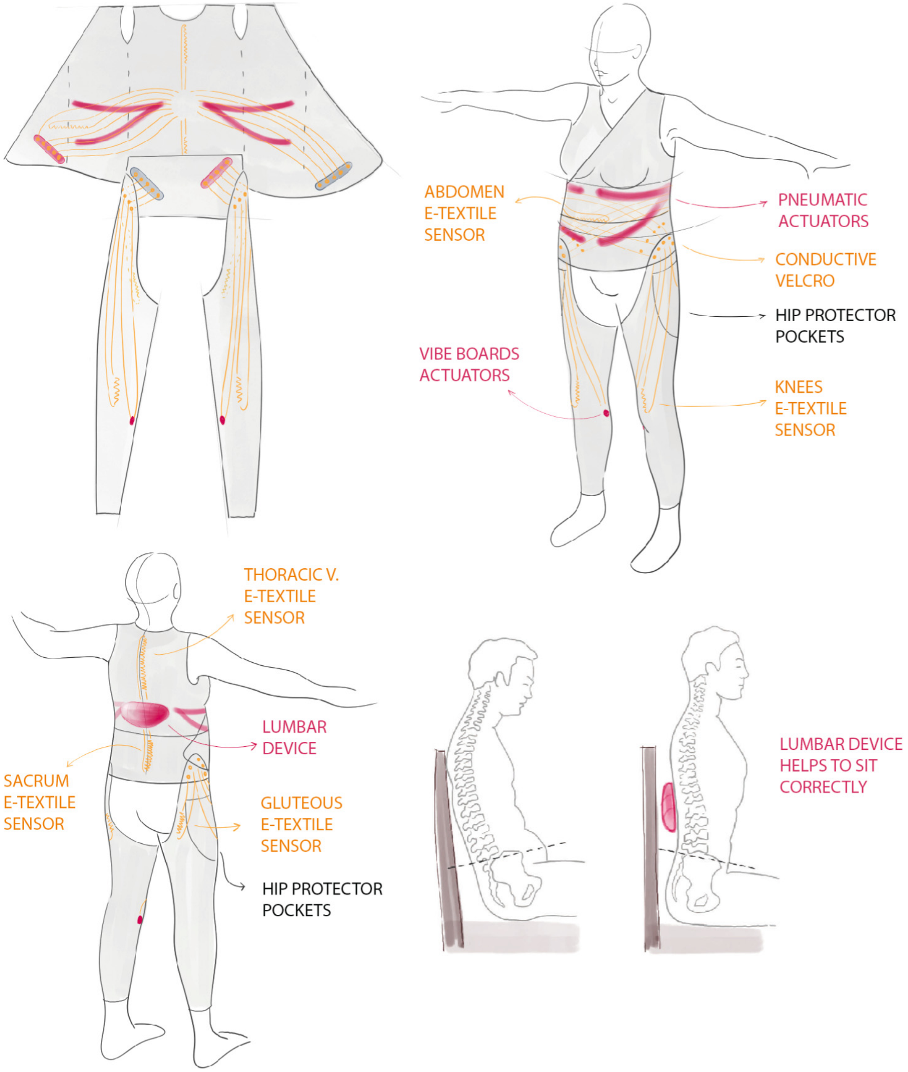

Fig. 1. Full-body smart suit scheme.

As previously investigated by Gioberto, Compton and Dunne [14], by attaching it to body areas in flexion and extension, body motion and position can be recognized and quantified. The Micro Controller Unit (MCU) provided for the operation of the system will read the data and activate the soft actuation. In such a simple way, the system can detect walking (alternating knee data detections) and sitting/standing position (simultaneous knee data detections). In addition, by placing a pair of sensors in the hip area, the system can recognize prolonged knee flexions and wrong weight unloading while standing: electrical resistance on knees' sensors would decrease while resistance at hips would remain steady. In this case, to alert the wearer and suggest the correction, the MCU will engage the vibrational motors placed on the knee area (Lilypad Vibe Boards), sewn between the fabric layers of the suit's lower part. Thus, the system (consisting of the upper and lower garments performing in a coordinated manner) would detect: misalignment during sitting and standing; relaxation of the abdomen; and the amount of body movement. Therefore, we chose to place the Stretch Sensor—Statex 235/36 2-ply HC+B conductive thread on Lycra stretch fabric—along the spine's thoracic section, on the abdomen, and, in pairs, on the knees and hips (see Fig. 2).

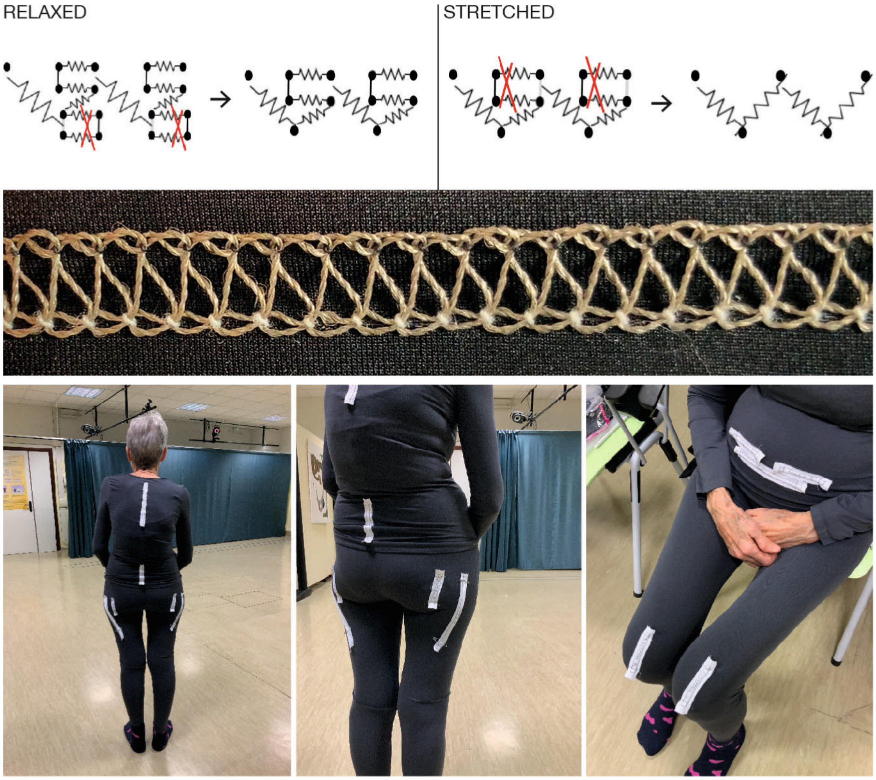

Fig. 2. Machine-stitched E-textile Stretch Sensor and body positioning. The pattern elongation causes a progression of contacts which gradually shorten the circuit, i.e. the electrical resistance measured at its ends. The longer the string (and the loop pattern recurrence), the more short-circuits induced by its elongation—and more effective the detection. For accurate details please refer to Gioberto, Compton and Dunne's study [14].

2.2 Soft Actuation

As abovementioned, when the MCU detects improper bending and trunk anteflexion a pneumatic soft actuator will be activated providing the corrective stimuli to the wearer, that must be perceptible for a certain amount of time. In order to prevent monotony, which is the enemy of receptivity, they should vary in intensity. We assigned this function to shape-transition pneumatic actuators (to be sewed inside the shirt), so that the air injection compresses the targeted body area and induces variable tones of stimulation. The alerting/stimulating engagement would vary as needed: *gentle*, at first, as a soft warning; *deeper*, as further warning; *intense*, when the wearer persists in improper posture.

Fig. 3. Soft actuators prototypes.

Along with specialists of San Marco Rehabilitation Centre of Vicenza (Italy), we decided to place a pair of Y-shaped actuators on the abdomen area, between the chest and the lower abdomen. As tested, the stimulus would generate a more instinctive (hence, natural) corrective reaction—in addition, haptic perception and proprioceptive effect would be more intense. The structure and material of these actuators are crucial. The model we refer to is the *aeroMorph* [16], an advance study on origami patterns design for shape transition materials through air injection. As tested, by heat-printing strings of pre-tested geometric shapes onto one side of the actuator, it is possible to control bending during air injection.

Test-actuators have been prototyped in two versions (see Fig. 3): a lighter one, made of two layers of white TPU; and a stronger one, made of black TPU and a Cordura-coated side—to verify if a thicker layer could deflect the expansion inward, and make the stimulus more perceptible on the targeted body area. For each version, two models have been developed: a *six heat-printed diamonds* model, from which a segmented but yet fluid bending was expected; and a *sixteen heat-printed diamonds* one, to result in a spiral bending. The goal is to deliver a stimulating and yet not uncomfortable kinetic response, so it is crucial to avoid pumping air at pressures that require high-powered, bulky pumps.

The *six* and *sixteen diamonds* samples reacted to the air injection in a more suitable manner for the desired function, and with deformations compatible with the fabric and cut of the garment to be fixed into. We tested them along with the stretchable fabric and the human body (the shapes of which, especially if in the presence of adipose tissue, could mitigate, if not neutralize, the stimulus to be induced).

2.3 Garment Design

In order to find the proper balance between fabrics and components (acceptable to the wearer) we opted for the *layering system*, as recommended by Timmins and McCann [17]. The tailoring of both the upper and lower part of the system requires the assembling of three textile layers. A fourth 'layer' (not strictly textile) will be connected to the whole system through the upper part. Therefore, we designed:

- the intimate layer ('second skin') made of bi-elastic cotton (90% cotton, 10% elastane) which is soft, warm and gentle to the skin;
- the middle layer ('e-textile') made of Lycra where the sensor circuits are sewed (function accuracy takes priority over softness);
- the outer layer ('actuator-aesthetic') made of colored Lycra, where actuators adhere to its inner side—pneumatic ones in the upper garment and vibe boards in in the lower one (the outer side, essentially aesthetic, is provided with a *soft socket* in the lumbar area of the shirt to allow connection to the fourth 'layer', and side-pant pockets for optional hip protectors housing);
- the intelligent layer (not strictly a textile layer), a *plug-and-play* lumbar device to be attached to the soft socket of the upper garment (see Fig. 4). It hosts mechanics and electronics and is protected by an ergonomic soft shell designed to support proper sitting. Internally, there will be eight primary components at work: i) a MCU: for the first version of the system, we opted for SparkFun ESP32 Thing board which integrates

ii) a Bluetooth module; iii) an air micro-pump (diameter: 27 mm; length: 60 mm; weight: 60 g, noise: <55 db; voltage: 6.0 V; emission: 2 l/min); iv) a 3.7 V (7.4 W, 2000 mAh) battery pair in series; v) a solenoid valve; vi) a pressure sensor and vii) additional Printed Circuit Boards (PCB) for transistors and microresistors placement (required for sensor signals readability); and viii) a USB input for recharging.

The suit's full-version is designed as a modular combination: wrap shirt, lumbar device, waistband, and pant-legs—whose design is not detailed in this paper. Cuts and shapes are the result of multiple wearability tests on elder female users in attempt to find the best mediation between wearability, usability, acceptability and garment performance.

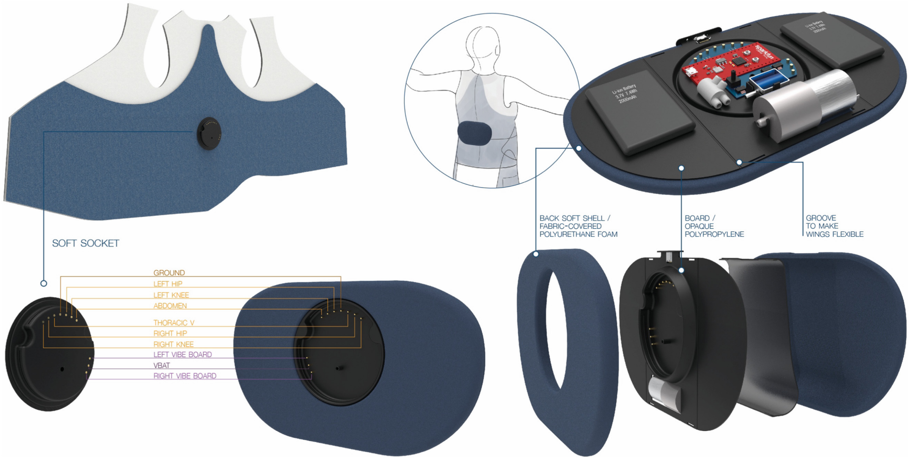

Fig. 4. The 'intelligent layer'(socket and lumbar device).

3 Results

3.1 Experimental Analysis

To run the experimental analysis, we used a standard stretchable suit functional for keeping sensors exposed and easily reachable by digital multimeter probes. The tested volunteer was 75 year old woman with thoracic hyperkyphosis, asymmetrical shoulders, and protracted abdomen. As agreed with physiatrists, we tested:

- One thoracic vertebral sensor: 15 cm, vertical, along the thoracic section of the spine—from T1 to T8 vertebrae—to detect back slouching;
- One sacral sensor: 10 cm, vertical, along the sacral section—from L4 to Sacrum—to support /confirm data from the thoracic vertebral sensor;
- One abdomen sensor: 15 cm, below the navel, horizontal, to detect abdominal relaxation;

- Two hip sensors: 15 cm, vertical, between the gluteus maximus muscle and the biceps femoris longus muscle, to detect sitting, standing, and motion along with the knee sensors.
- Two knee sensors: 5 cm, vertical, between the quadriceps femoris tendon and the patella, to detect sitting, standing, motion, and incorrect weight unloading along with the hip sensors.

The technical protocol combines the employment of the digital multimeter with postures and steps analysis processed by a Vicon optoelectrical motion capture system—to verify the effective extent of movement that produced the Electrical Resistance (ER) variation. Data obtained from two sets of static poses and one moderate pace walk have been cross-referenced. Tables 1, 2 and 3 show the ER of each stretch sensor in transition from the first static (upright/straight) pose to the second (natural/relaxed) one, and the value of variation (see Fig. 5). As expected, drops in ER in the *thoracic v.* (−1.8 Ω), *sacrum* (−0.6 Ω), and *abdominal sensors* (−1.2 Ω) were recorded when the volunteer indulged in incorrect posture. The volunteer's motion was slight, so as were the recorded variations.

The next static detections relate to: standing straight toward standing relaxed (we asked the volunteer to go back to her natural pose while slightly flexing her knees). We recorded decrements in ER in all sensors. The most indicative decrement (higher than 1 Ω) was observed at the *thoracic v.*, *abdomen*, and *knee*. Even if numbers cannot be intended as conclusive, expectations about the stretch sensor's mechanical response and its reliability in most body segments were met [18].

As a completion of the static poses analysis, we crossed standing upright and sitting straight. As expected, most values decreased (the small rise in *thoracic v.* resistance indicates that, while sitting, the volunteer improved spinal alignment slightly). The data that met expectations were detected at the knee (−2.6/−2.4 Ω for 90° flexion) and hip (−4.2/−4.3 Ω) sensors. The sacrum was practically irrelevant.

Table 1. Static posture detection: sitting.

Sensor	Sitting upright	Sitting relaxed	ER variation
Thoracic V	56,2 Ω	54,4 Ω	−1,8 Ω
Sacrum	27,5 Ω	26,9 Ω	−0,6 Ω
Abdomen	28,3 Ω	27,1 Ω	−1,2 Ω
L HIP	46,1 Ω	46,1 Ω	–
R Hip	45,6 Ω	45,6 Ω	–
L Knee	17,6 Ω	18,1 Ω	+0,5 Ω
R Knee	17,2 Ω	17,8 Ω	+0,6 Ω

The legs' sensor-equipment also serves as a soft motion recording instrument, allowing to monitor the degree of activity or sedentarism of the wearer without overloading the MCU with additional data from Inertial Measurement Unit (IMU) sensors. Thus, we also

Table 2. Static posture detection: standing.

Sensor	Standing straight	Standing naturally (flexed knees)	ER Variation
Thoracic V	55,8 Ω	54,4 Ω	−1,4 Ω
Sacrum	28,0 Ω	27,9 Ω	−0,1 Ω
Abdomen	28,9 Ω	27,2 Ω	−1,7 Ω
L Hip	50,3 Ω	50,2 Ω	−0,1 Ω
R Hip	49,9 Ω	49,7 Ω	−0,2 Ω
L Knee	20,2 Ω	18,8 Ω	−1,4 Ω
R Knee	19,6 Ω	18,5 Ω	−1,1 Ω

Table 3. Static posture detection: standing vs sitting.

Sensor	Standing straight	Sitting upright	ER variation
Thoracic V	55,8 Ω	56,2 Ω	+0,4 Ω
Sacrum	28,0 Ω	27,5 Ω	−0,5 Ω
Abdomen	28,9 Ω	28,3 Ω	−0,6 Ω
L Hip	50,3 Ω	46,1 Ω	−4,2 Ω
R Hip	49,9 Ω	45,6 Ω	−4,3 Ω
L Knee	20,2 Ω	17,6 Ω	−2,6 Ω
R Knee	19,6 Ω	17,2 Ω	−2,4 Ω

tested the sensor's accuracy for this function (Table 4, see Fig. 6). First, we examined the *hip* sensor. While static, the measured ER was 36 Ω. While walking, it went from 34.2 Ω (min) to 38.6 Ω (max). Peaks relate to maximum flexor traction (initial swing phase), and relaxation (terminal swing phase). The ER variation (4.4 Ω) met expectations [18]. The recurrence of such a value variation will enable the MCU to detect and quantify the motion while wearing the system. Similarly, the *knee* sensor was tested. While walking, the resistance oscillated from 18.3 to 20.4 Ω. (19.2 at rest). This variation (2.1 Ω) was sufficient for the purpose.

At the conclusion of the session, it can be assumed that, by cross-referencing the data detected by the e-textile stretch sensors, the intelligent layer will be able to distinguish right from wrong postures, and walking from sitting [18].

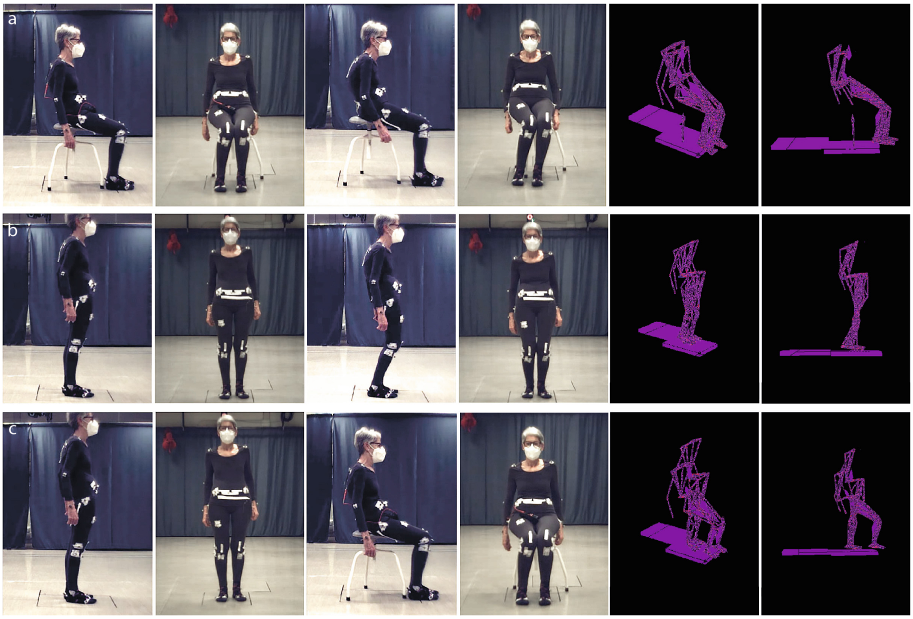

Fig. 5. a) sitting upright and relaxed compared; b) standing straight and naturally (with flexed knees) compared; c) standing straight and sitting upright compared.

Table 4. Walking detection.

Sensor	Static	Swing (max flexion)	Stance (max extension)	ER Variation
R Hip	36,0 Ω	34,2 Ω	38,6 Ω	4,4 Ω
R Knee	19,2 Ω	18,3 Ω	20,4 Ω	2,1 Ω

Fig. 6. Walking detection.

3.2 The Pneumatic Actuators: Qualitative Experimental Analysis of the Tactile-Compressive Function

Qualitative experimental analysis was based on subjective reports. While we were able to assess the proper actuators' kinetic response to the transit of air, we could not rely on objective protocols to measure a patient's sensation [18]. Our m. o. had to be sympathetic, i.e. the attentive listen to the volunteers and their physical and mental involvement through the experimentation. Tests were carried out in two phases: the first one with three volunteers—we tested different combination of actuators to verify which version and pattern is more perceptible—and the second one, with two patients in postural rehabilitation (social restriction imposed by the 2020/21 pandemic emergency has made contact with vulnerable people limited) by integrating the chosen actuators into the mock-up shirt as described in Sect. 2.3 *Garment design.*

The first volunteer (v.1), aged 75 years, suffered from previous fall episodes, she has gynoid body conformation and adipose tissue in the contact areas of the actuators (see Fig. 7).

Test 1: during both standing and sitting, v.1 put on the six diamond samples in pairs between two Lycra shirts—first the light version, then the reinforced one (see Fig. 7). She was asked to indicate the points where the given stimulus was most pronounced when we injected air and to refer her sensation. She reported that with both versions there is a clear sensation of pressure is perceptible, and spread around the belly. Nonetheless, the white one [light] displayed a more peculiar touch.

Test 2: v.1 was asked to try both versions with sixteen diamonds, and again indicate which spots were most stimulated. She reported she felt an air flow very similar to the previous test, but this time there was a kind of slightly stronger manipulation, especially with the black version [Cordura-coated], under the chest and the navel [i.e., at the extremities of the actuator, where the shrinkage is most detectable—especially in the reinforced samples]. While in doubt about which density was preferable (light or strong), v.1 preferred the sixteen-diamond model for each version. V.1 reported three substantial factors: i) a preferable *fit to the body* was perceived (whereas the six-diamond samples provided the sensation of detaching from the torso as the volume increased); ii) a vigorous *manipulation* was perceived in the central abdominal area; iii) on a merely aesthetic perspective, the pattern emerging from the fabric looked more graceful than the *sausage pattern* generated by the six-diamond sample—the defect was visible in both versions, implying that the Cordura coating did not drive the deformation inward as effectively as expected.

The session was repeated three days later to let receptors' memories vanish. This time we tested the light and Cordura-coated versions of each sample in combination. We repeated test 1 and 2 twice. The second time we gave v.1 the handpump so that she could take control of the air injection and ponder the sensory involvement by herself in proportion to the pressure and volume of the pumped fluid. At the conclusion of the new session, uncertainty about materials persisted (after each new test, v.1 reported she *felt better* the lighter version). On the other side, impressions regarding the number of diamonds were strongly confirmed: lastly, v.1 reported that the folds of the sixteen-diamonds were more stimulating.

Fig. 7. First phase tests; untied samples test with volunteers.

We turned to volunteer 2 (v.2), aged 81 years old, who suffered from several previous fall episodes. She has android body conformation, taut belly without adipose mass. We proposed her the same sequence of tests. Her impressions were almost identical.

V.2 reported she felt more affected by the sample with sixteen diamonds and between black and white [light and reinforced] she didn't feel much difference. She felt the same pressure in the same spots. Eventually, she chose the white option because it made her feel less bulky, it is less rigid underneath the fabric, and it seemed to be less awkward.

The final volunteer (v.3), younger, aged 71, with one fall episode without injuries, android conformation, soft bellied but still toned, confirmed the same impressions.

Although leaving us hesitant about the usefulness of Cordura coating, tests on free samples (not yet sewn into the mock-up shirt) provided us unanimous confirmation: size, shape, and pattern withstand tests on different body conformations: the targeted body area—whether taut, soft with adipose mass, or relaxed—received the fluid stimulation with an intensity that met expectations.

Fig. 8. Second phase tests; test of the mock-up with patients.

We then proceed with testing on patients at the rehabilitation centre (see Fig. 8). Thus, we basted the mock-up shirt, integrating the sixteen-diamond samples: the light version on the left side, and the reinforced one [Cordura-coated] on the right.

Patients undergoing postural rehabilitation therapy were 71 (p.1) and 64-year-old (p.2). The physiatrist started the sequence of tests by personally adjusting the air pressure, and asked p.1 and p.2 to report impressions.

As per P.1's report: the pressure was felt more strongly on the left [where there the lighter sample was]; the actuation, although *audible*, did not suggest how to correctly posture, even if, admittedly, a sort of *urge to react* was felt; on the end, the tightness of the garment was quite invigorating.

As per P.2's report: a more distinctive manipulation was detected on the left and middle side of the abdomen; the actuation was indeed pretty loud but did not keep the torso upright as it should [being accustomed to rigid orthopaedic corsets, P.2 envisioned a 'passive' administration, i.e. a shirt to keep her torso in an upright position without her intervention or effort]; once the shirt was taken off, it felt like there was still a *trace* of the actuation around the torso, like a *tactile memory* in that specific area.

Reports were consistent with expectations. The physiatrist explained that both patients were neither prepared nor, more importantly, instructed on how to react physically to the induced stimuli. They were brought into contact with the product deliberately without any previous mediation. This gave rise to their doubts about the 'active' re-educational function. If this smart garment is ever adopted as a therapeutic device, it will be up to the physician to prescribe and explain the proper physical response following the stimulus, which differs from case to case [18].

4 Conclusion

Tests have been run on a limited user sample due to the Covid-19 emergency. Albeit not statistically conclusive, they suggest the way to a new dimensional approach, both for rehabilitation and prevention. According to physiatrists, this assistive principle may indeed make sense: the neuromotor stimulus provided by the fluid injection would define, in the mid-term, an *intimate user-device language* that trains postural education—in a conscious way at the beginning until becoming almost irreflective, natural with practice [18]. Thus, the corrective reaction induced by the air flow would gradually reinforce muscles, consolidating better posture over time and, as a result, limiting the risk and the fear of falling.

In conclusion, the project's aims are several. First, it seeks to provide a comprehensive geriatric tool to physically and psychologically rehabilitate patients and prevent further falls. Second, to probe the effectiveness of a therapeutic pneumatic actuation as a tool for postural re-education. Third, to explore the effectiveness and durability of a new user-device dialogue through targeted stimulation on sensitive areas. Fourth, to extend physical therapy to patients' homes and remotely monitor their progress through a patient-therapist smartphone application—which has not been detailed in this paper. Fifth, to shorten recovery and reduce the risk of new falls—meaning, in turn, reducing direct and indirect costs, both for the individual and health systems.

Moreover, if ever needed, this paper also seeks to emphasize how a multidisciplinary approach, involving specialists, therapists, and end-users, is the key to design remote healthcare devices that are truly centred on user needs—and somewhat innovative compared to current tools and practices.

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