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ERGONOMICS OF GESTURE: EFFECT OF BODY POSTURE AND LOAD ON HUMAN PERFORMANCE

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Abstract

Smart clothing or “intelligent textile” represents the new class of wearable textile design era 2.0 with interactive technologies, intended to be attractive, comfortable and ‘fit for purpose’ for the identified user. Smart clothing offers a unique opportunity to monitor soldier’s performance in terms of training, injuries, and psychological status monitoring in an ecological and non-intrusive approach.

A good design of smart clothing for soldiers is a crucial element for safety, security, and ergonomic factors. These must be addressed together with the traditional wearability and comfort ones. Anthropometric and gender considerations, as well as textile requirements are to be included into the design core. Physiological, ergonomical and biomechanical evaluation of soldier’s performance were considered permitted us to define the final functional cloth.

A general research approach is discussed in Chapter 1 to describe and identify different research methodologies and their application, as well as the relation of this work to the research domain of smart textile systems, are described and identified.

Chapter 2, describes the effect of load on body posture and load on human performance describes (civil and military). This part of research is based on a systematic literature review based on search engine databases (Web of science and PubMed) focused on identify the impact of load carriage on the mobility of military personnel and civils.

Chapter 3 focuses on the use of smart clothing (civil and military).

In Chapter 4, all the co-design workflow for designing our smart clothing starting from an anthropometric approach collected on total of 1615 male Belgian soldiers aged between 18 and 35 years were investigated. In that process, we can distinguish two main macro areas to establish the product’s requirements: the technological issues and the design issues. Both areas are essential for the product design. While the first is related to biosignal sensor technologies, the second includes physical and design factors such as anthropometry and gender issues, body positions, adherence, elasticity and wearability of the garments.

The smart t-shirt is capable of monitoring in real time the heart rate (ECG) and the 3D body accelerations of the trunk. Bluetooth communication allows the real-time communication with a custom-made APP suited for the purpose. The information can be either stored or immediately transferred to a nearby computer for the successive analysis.

In Chapter 5, new algorithms for monitoring performance are presented. These algorithms are addressed to measuring posturographical and physiological parameters of the soldier. The last Chapter presents the conclusions and future developments.

To my family

Acknowledgement

After three years of doctoral research, I am pleased to write this dissertation. These three years were an excitement research where I discovered myself and I performed what I like more to do in my life “research”.

During the last three years I met a lot of people that transmitted me the knowledge and the passion to do research.

First, I would like to say thanks to ABAL Department and especially Prof. Marc Pirlot, head of Department to support me on this project.

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There are a lot of people that I met during my PhD travelling and conferences that I am not able to list below.

Finally, I cannot exclude my family that supports my choice to be a researcher.

The most beautiful experience we can have is the mysterious. It is the fundamental emotion that stands at the cradle of true art and true science.

Albert Einstein

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List of Publications

Scataglini S., Truyen E., Perego P., Gallant J., Tiggelen D.V., Andreoni G., “Smart Clothing for Human Performance Evaluation: Biomechanics and Design Concepts Evolution” in 5th International Digital Human Modeling Symposium, Germany, Bonn, 2017.

Scataglini S., Truyen E., Perego P., Gallant J., Tiggelen D.V., Andreoni G., “Assessment of Human Balance Due to Recoil Destabilization Using Smart Clothing” in Goonetilleke R., Karwowski W. (eds) Advances in Physical Ergonomics and Human Factors. AHFE 2017. Advances in Intelligent Systems and Computing, vol 602. Springer, Cham.

Scataglini S., Truyen E., Perego P., Gallant J., Tiggelen D.V., Andreoni G., “Smart clothing for heart rate variability measures in military” in HBIM Journal, vol 1, July 2017.

Scataglini S., Truyen E., Andreoni G., Gallant J., Tiggelen D.V., “Anthropometric and postural control interactions during shooting”, Poster in 15th ESM (Expert Scientific Meeting on Load Distribution Measurement), Lisbon, Portugal, 27-30 July 2016.

Scataglini S., Andreoni G., Truyen E., Warnimont L. Gallant J., Tiggelen D.V., “Design of smart clothing for Belgian soldiers through a preliminary anthropometric approach”, in Proceedings 4th DHM Digital Human Modeling, Montréal, Québec, Canada, 15-17 June 2016.

Scataglini S., Truyen E., Gallant J., Tiggelen D.V., Andreoni G., “Monitoring the Belgian soldier’s performance through the use of smart clothing” in Proceedings International Congress of Physiotherapy, Brussels, Belgium, 30 January 2016.

Scataglini S., Truyen E., Gallant J., Tiggelen D.V., “Effect of Recoil Destabilization on Soldier Performance: Results of the study of sway path evolution with time” in Proceedings ESB, Prague, 2015.

Scataglini S., Andreoni G., Gallant J., “A review of smart clothing in Military” in Proceeding WearSys '15 Proceedings of the 2015 workshop on Wearable Systems and Applications, ACM New York, pp.53-54, NY, USA, 2015.

CHAPTER 1

Introduction

1.1 Scientific context of reference

Evaluating human performance and identifying critical factors is a challenge due to the high number of parameters of the problem, their strong interdependence, and the multiple degrees of freedom. Stress, training, fatigue, load, and environmental conditions have an influence.

Normal balance requires control of both gravitational forces, to maintain posture, and acceleration forces, to maintain equilibrium [1]. Acceleration forces may be generated from within the body as the consequence of voluntary movement or from outside as the result of unexpected disturbances, such as a push. Balance control is the need to maintain the body's center of mass (COM) within manageable limits of the base of support (BOS) as in standing, or on track to a new BOS, as in walking or running [2]. Together, the postural and equilibrium components of balance control ensure stability of the body during widely differing activities. The exact demands on the balance control systems are determined both by the task itself and the environment in which it is performed.

The instruments that can be used to evaluate the human factor are numerous. Electromyography, pressure plates, and force plates can be used together with 3D motion capture in a biomechanics lab to analyze the kinematics and kinetics of the human body.

We didn't have information about the changes in the human factor due to stress, fatigue, and external non-physical perturbation during a simple task.

Nowadays, with the introduction of the wearable devices we have the possibility to implement this measurement (heart rate, respiratory rate, acceleration...) in a smart textile.

This thesis was born thanks to a collaboration between the Royal Military Academy of Brussels and the Politecnico of Milano with the aim of investigating ergonomics of gesture in human factor, focusing on the soldier. The thesis is part of a Belgian Defence project called HF-26. It focuses on the effect of loads on the soldier and investigates the mechanism to prevent performance decrements due to the physical overload, environmental and operational stresses, and musculoskeletal injuries. There is also a collaboration between the Military Hospital Queen Astrid (MHQK) and the Royal Military Academy (RMA) in the framework of this project.

1.2 Research Design

Starting from the context of the reference the research method was identified and applied to the thesis development.

1.2.1 Research methodology

Methodology is a systematic, theoretical analysis of the methods applied to a field of study. It comprises the theoretical analysis of the body of methods and principles associated with the branch of knowledge [3]. In research theories, two methods of reasoning known as deductive and inductive reasoning describe how the theories, hypotheses and observations can be related to form a scientific approach to the research problem.

In both cases, theory is crucial. But the relationship between theory and research differs for each approach.

The deductive approach starts with the theory, moving from general to more specific, as the numerical estimation and statistical inference. In this approach, the researcher studies what was done by others, reads, and tests the hypothesis emerging from theories making observations (Fig.1.1).



Fig.1.1 Deductive research

The inductive process is the opposite, moving from specific to the general. In this case the researcher starts from a specific observation and then, he/she moves from a specific to a broader generalization of the theories (Fig.1.2).



Fig.1.2 Inductive research

Both approaches can be also complementary. Researchers can apply both, starting from the empirical studies to the hypotheses or from a real world to validate the hypotheses and then develop a more general theory.

Pierces abduction model is the process of explanatory hypotheses. It is only a logical operation which introduces any new idea [4]. Abduction invents or proposes hypotheses. Then induction and deduction came to play. Deduction explicates the hypotheses while induction test establishes the hypotheses.

Deductive and inductive methods are commonly by applied in chemistry, physics, and mathematics. The abductive approach is more explicative in engineering science.

New research methods, as design theories in design science research are a perspective statement and outcome specification from which the implication can be drawn: if a system is constructed according to (the design) theoretical

prescription, then the system will behave (have outputs) as specified in the theory [5]. A multimethodological approach proposed by Nunamaker, Chen and Purdin [6], contains four more strategies (Fig 1.3) named theory of building, experimentation, observation, and the system development strategy in the center. Each of these strategies contains several stages that can help the researcher to create, test, observe, verify, and validate the knowledge.

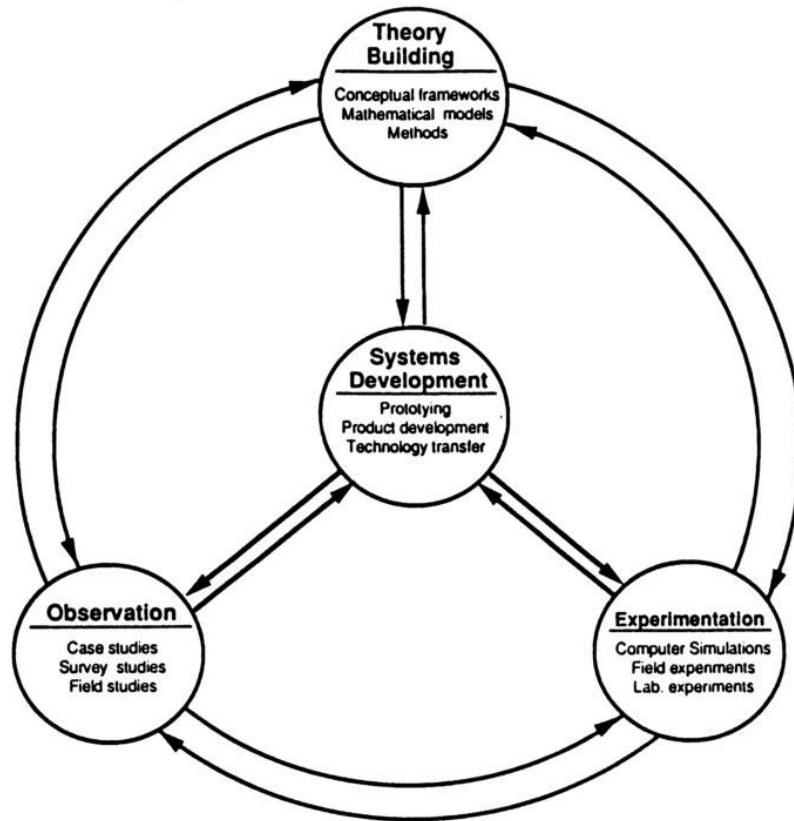


Fig.1.3 Nunamaker's multimethodological approach to information systems (IS) research

Deductive and inductive methodologies remain used in the different stages of methodological approach but in a different flexible manner.

Research can be classified as pure or as applied research [7], as a perspective of application (laboratory experiments), from the perspective of objectives, a research can be descriptive, correlational, explanatory, and finally from the perspective of inquiry mode, research can be quantitative and qualitative.

1.2.2 Research method applied to the thesis structure

The conducted research is purely based on the multimethodological model (Tab 1.1) adopted from Nunamaker and Chen [6] presented in the previous section.

Multimethodological approach	
Observation	Literature review and questionnaire
Theory Building	Inductive methods
System Development	Concept design
Experimentation	Lab Experiment

Tab1.1 Multimethodological approach

Inductive methods were used to identify the design concept based on literature review and the conceptual and theoretical framework. Iterative study during the system development with laboratory experimentation permitted to redefine the garment and identify the final product.

1.3 Research Overview

The research process overview gives an idea of the steps involved in the complete PhD research, that can be described in three macro areas.

The first part investigates the context of the reference, identifying the effect of load on body posture and load on human performance (civil and military) through a systematic review based on search engine databases (Web of science and PubMed) focused on identifying the impact of load carriage on the mobility of civilian and military personnel.

Next, the collected data goes to the identification of the existing technologies (smart technologies) for monitoring performances in military.

Having identified the key concepts for the research, successive steps are necessary to investigate the user and the user needs (fig.1.4).

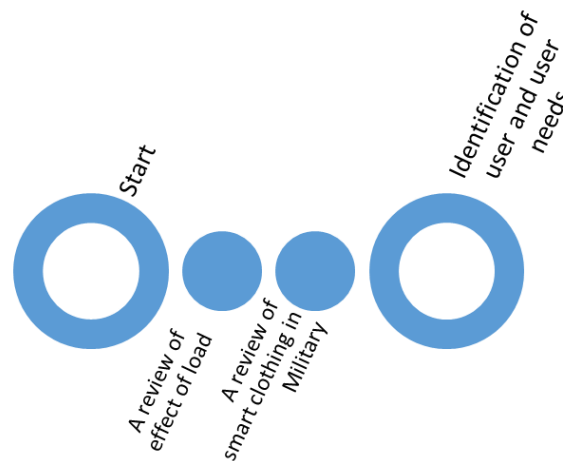


Fig.1.4 User needs and user scenario

The second part presents all the steps involved in the co-design workflow for the design of functional smart clothing for human performance evaluation. Two prototypes were realized. Iterative studies on the co-design workflow permitted us to define the final functional cloth that was used in the third step for

monitoring soldier's performance in term of training, injuries, and physiological status monitoring (Fig.1.5).

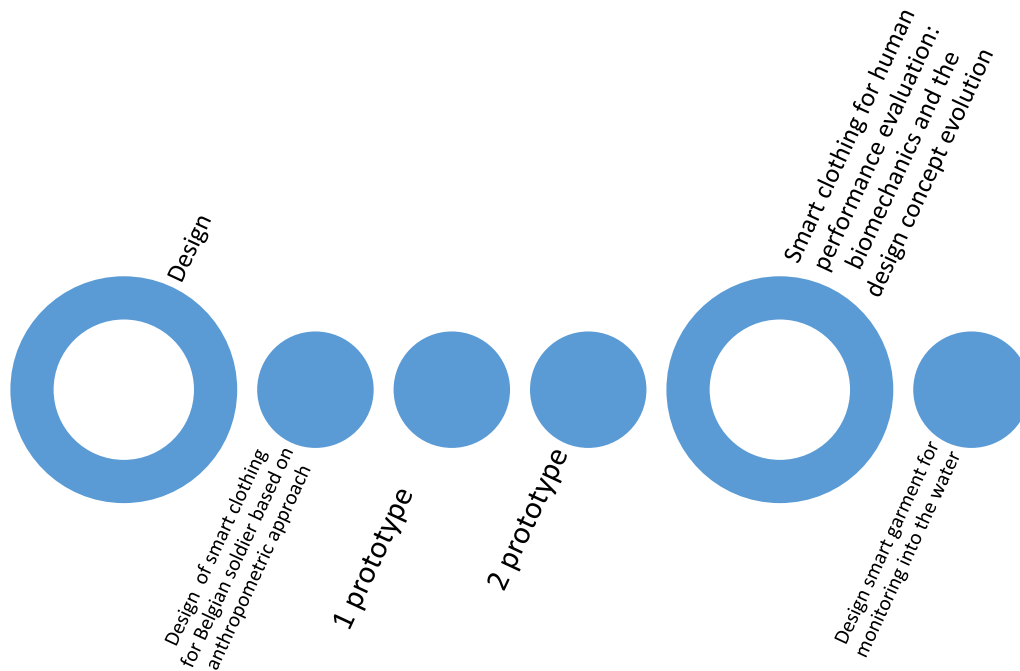


Fig.1.5 Co-design concept and prototyping

The third part is dedicated to the definition of new algorithms for monitoring soldier's performance taking in consideration the biomechanical evaluation of user gestures such as fitness, shooting, climbing, cycling, etc. Physiological and biomechanical parameters of the soldier's performance, wearing the smart clothing, were monitored, and quantified permitting the redesign and the technological refinement of the garment (Fig.1.6).

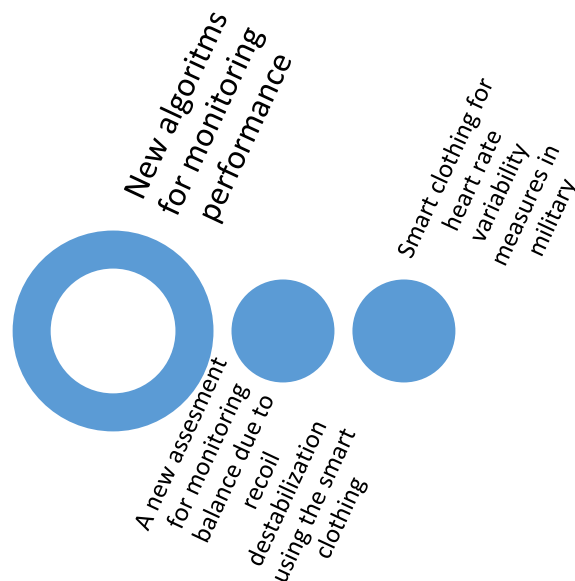


Fig.1.6 New algorithms workflow

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CHAPTER 2

Effect of body posture and load on human performance. State of the art

2.1 Introduction

This part investigates the context of the reference, identifying the effect of load on body posture and load on human performance (civil and military). The research is based on a systematic review using search engine databases (Web of science and PubMed) of the research conducted in last 25 last years in the field of the impact of load carriage on the mobility of military personnel and civilians.

2.2 Load carriage and posture in civilian context: a systematic review of the literature

2.2.1 Methods

Two databases were used to search for relevant original research article using the keywords “load carriage and posture”. The table below (Tab. 2.1) describes the database and keywords that were used. Following removal of all duplicates, articles were subjected to the specific inclusion criteria, these being (a) excluded the military field; (b) involving human participants carrying an external load; (c) excluded review; (d) excluded the effect of load carrying on metabolic cost.

Database	Search Terms	Filters	Number after inclusion	Number after exclusion
PubMed	load [All Fields] AND carriage [All Fields] AND ("posture"[MeSH Terms] OR "posture"[All Fields])	Military Review Metabolic	87	13
Web of Science	load [All Fields] AND carriage [All Fields] AND ("posture"[MeSH Terms] OR "posture"[All Fields])	Military Review Metabolic	148	15

Tab.2.1 Details of literature search: database used, search terms and inclusions filters

2.2.2 Results

From the primary research, a total of 87 and 148 articles were identified based on PubMed and Web of Science respectively. After application of the exclusion criteria, 13 and 15 articles were selected based on PubMed and Web of Science respectively. The two databases had six common articles. A total of 22 articles were thus selected for this review (Fig.2.1). Table 2.2 shows the methodologies and major findings.

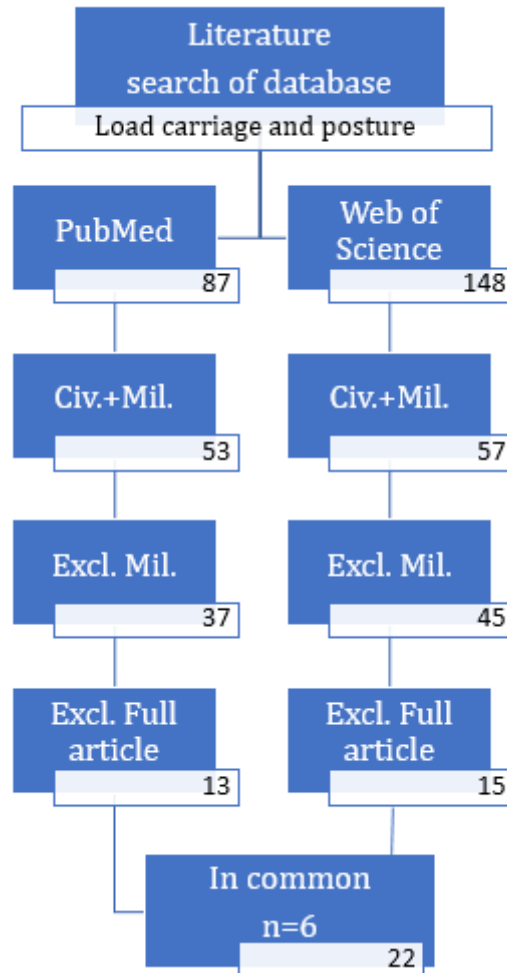


Fig.2.1 A flow chart of the literature review process

Tab.2.2 Summary and critical appraisal of articles included in this review.

Comment: the number of the study is linked with the bibliography					
Study	Aim	Participants	Load	Task	Findings
1	Evaluate the immediate responses of varying backpack loads on cranio-vertebral angle (CVA), sagittal shoulder angle (SSA) and trunk forward lean (TFL).	Males (18-25) years.	no backpack, carrying backpack of 5%, 10%, and 15% of body weight (BW)	Sagittal photograph was taken of the area of the body corresponding to spinal angle during each of these test conditions to allow for later analysis of postural deviations. Comparisons of the mean deviations of the different postural angles from baseline and between test conditions were made using ANOVA at $p \leq 0.05$.	There was a trend toward a decrease in the CVA and TFL with increasing backpack loads. Specifically, a significant decrease was seen for TFL at 10% and 15% BW loads when compared with no load condition. In contrast, the decrease in CVA was only significant between no load condition and 15% body weight load. The SSA remained unchanged with backpack weight within 15% BW.
2	Investigate the effect of symmetric and asymmetric loading conditions on L5/S1 and lower extremity moments during stair negotiation.	22 college students	no load, 10% BW, unilateral load, 20% BW unilateral load, 10% BW bilateral load, and 20% BW bilateral load.	They performed stair ascent and stair descent on a three-step staircase (step height 18.5 cm, tread depth 29.5 cm) at preferred pace under five load conditions. Video cameras and force platforms were used to collect kinematic and kinetic data. Inverse dynamics was used to calculate frontal plane moments for the L5/S1 and lower extremity.	20% BW unilateral load resulted in significantly higher peak L5/S1 lateral bending, hip abduction, and external knee varus moments than nearly all other loading conditions during stair ascent and stair descent. Therefore, we suggest potential benefits when carrying symmetrical loads as compared to an asymmetric load to decrease the frontal joint moments, particularly at 20% BW load.
3	Evaluate postural and load distribution differences between a traditional backpack (BP) and a non-traditional backpack (BTP) in a young adult population.	24 healthy adults	no load and with 15% and 25% of their BW.	Using a 3D motion analysis system, they completed both static stance and walking trials on a treadmill using the two different backpacks.	There was a significant difference in trunk angle, head angle, and lower extremity joint mechanics between the backpack and load conditions during walking ($p < .05$). Notably, relative to the No Load condition, trunk angle decreased approximately 148 degrees while head angle increased approximately 138 degrees for the BP 25% state on average. In contrast, average trunk, and head angle differences for the BTP 25% state were approximately 7.5 degrees and 7 degrees, respectively. There was also a significant difference in head angle from pre- to post-walk (p

					< .05) across backpacks, loads, and time. Taken together, the results indicate that the BTP more closely resembled the participants' natural stance and gait patterns as determined by the No Load condition. The more upright posture supported by the BTP may help reduce characteristics of poor posture and, ideally, help to reduce low back pain while carrying loads.
4	Investigate the most critical backpack load by assessing simultaneously the spinal curvature changes along the whole spine.	Male students	backpack load at 0, 5, 10, 15 and 20% of BW.	A motion analysis system was used to measure the curvature changes in cervical, upper thoracic, lower thoracic and lumbar regions with backpack load.	Results suggested that the most critical backpack load was 13% of BW.
5	Determined the influence of type of backpack shoulder strap on gait parameters and perceived exertion of young adults in a free-living normal walking speed.	25 young adults	without a backpack; with 1 strap; and with 2 straps	They underwent a self-selected normal speed walking for six minutes each under 3 testing conditions: without a backpack; with 1 strap; and with 2 straps. Selected gait parameters and perceived exertion were assessed	There was no significant difference in stride length, stride time, step length, step time, gait speed, and cadence among the three walking conditions. However, perceived exertions were significantly higher when the backpack was carried with 15% irrespective of 1 strap or 2 straps.
6	Investigated the effect of prolonged walking with load carriage on body posture, muscle fatigue, heart rate and blood pressure of the tested subjects.	10 healthy volunteers	different backpack loads [0% BW, 10% BW, 15% BW and 20% BW].	The change of body posture, muscle fatigue, heart rate and blood pressure before and after walking and the recovery of muscle fatigue during the rest time (0, 5, 10 and 15 min) were collected using the Bortec AMT-8 and the NDI Optotrak Certus.	The forward trunk and head angle, muscle fatigue, heart rate and blood pressure increased with the increasing backpack loads and bearing time. With the 20% BW load, the forward angle, muscle fatigue and systolic pressure were significantly higher than with lighter weights. No significantly increased heart rate and diastolic pressure were found. Decreased muscle fatigue was found after removing the backpack in each load trial. But the recovery of the person with 20% BW load was slower than that of 0% BW, 10% BW and 15% BW.
7	Understand how load impacts the vertical COM(TSYS) trajectory and clarify the impact	17 subjects	nine different loads ranging from 12.5% to 40% BW	Subjects walked on treadmill at a constant preferred walking velocity while nine different loads were	Results suggest that forward lean changed linearly with changes in load to maintain the COM-to-ankle and -knee vector orientations. COM vertical

	of forward lean as it relates to the dynamics of sagittal plane COM(TSYS) movement during stance with changing load.			systematically added and removed from a backpack. Kinematic data were collected using an Optotrak.	trajectory was maintained by a combination of invariants including lower-limb segment angles and a constant direction of toe-off impulse vector. The kinematic invariants found suggest a simplified control mechanism by which the system limits degrees of freedom and potentially minimizes torque about lower-extremity joints with added load.
8	Determine how variations in load mass affected the heart rate, posture and subjective responses of women during prolonged walking to provide evidence for a load mass limit for female recreational hikers.	15 female experienced recreational hikers (22.3 ± 3.9 years)	0%, 20%, 30% and 40% of BW.	Heart rate (HR), posture and ratings of perceived exertion (RPE) and discomfort were collected for 15 female experienced recreational hikers (22.3 ± 3.9 years) while they hiked for 8 km at a self-selected pace under four different load conditions (0%, 20%, 30% and 40% of body weight (BW)). Although HR was not significantly affected by load mass or walking distance, increasing load mass and distance significantly affected posture, RPE and discomfort of the upper body.	Carrying a 20% BW load induced significant changes in trunk posture, RPE and reported shoulder discomfort compared to the unloaded condition. The 20% BW load also resulted in a mean RPE rating of 'fairly light', which increased to 'hard' when carrying a 40% BW load. As load carriage distance, increased participants reported significantly increased shoulder, neck and upper back discomfort. Based on the changes to posture, self-reported exertion and discomfort when carrying loads of 20%, 30% and 40% BW over 8 km, it was concluded that a backpack load limit of 30% BW should be recommended for female recreational hikers during prolonged walking.
9	Analyse trunk-lower extremity muscle activities and trunk postural changes during the carriage of different backpacks.	19 students (21+/-3 years)	(1) unloaded standing, (2) 10% BW load (in the form of a backpack), (3) 15% BW load and (4) 20% BW load.	Bilateral rectus abdominis, erector spinae, vastus medialis and biceps femoris muscle activities were recorded using surface electromyography (SEMG), while trunk inclination, side flexion and rotation were measured by using VICON 250 during all standing modes.	The results showed that rectus abdominis muscle activities increased progressively and disproportionably as the backpack load increased. As for the trunk posture, almost the same backward inclination was adapted even with increasing backpack heaviness. Twenty percent BW backpack causes the most significant muscular and postural changes, so it should be avoided.
10	Quantify the kinematics of the spine and stature loss	6 healthy persons	17.5% of the participant's BW	Six healthy mates with no history of low-back disorders walked at their self-selected pace for 8,500m in with and	The load was reduced gradually during the task. The loaded condition produced a stature loss twice that observed in the unloaded condition.

	induced by the asymmetric load carriage.			without a standard Royal Mail bag (model MB36).	Increased forward leaning (up to 6 degrees) and lateral bending of the spine (up to 12 degrees) was observed with load. Thoracic adjustments occurred in the sagittal plane, changes in the lumbar area occurred in the frontal plane. The data provided evidence against mailbag designs in which the workers cannot alternate the side of the mailbag.
11	Determine if spinal curvature and posture were affected by mild fatigue in load carriage.	25 healthy females	9 kg backpack	They carried a 9-kg backpack at 1.79 m/s for 21 minutes around a 200-m circuit. The pack had spring-loaded displacement rods intended to measure displacement from the pack to the spine. Subjects were filmed (60 Hz) and displacement data were collected during minute 3 (rested condition) and minute 18 (fatigued condition).	The thoracic to lumbar region cubic curve significantly increased as subjects fatigued. Rested trunk and head angles were not significantly different from the fatigued condition. Trunk and head angles were not indicative of spinal curvature at 18 minutes; therefore, they may not be the best measures of fatigue during load carriage.
12	Compare the differences in lumbosacral spine forces under varying backpack loads.	10 male subjects	no load, with 15% BW and with 30% BW.	Data acquisition was carried out using a 5-camera Vicon motion analysis system and two Kistler force plates. Ten male subjects with similar weights, height and age were recruited for this study.	When they walk with heavier backpack load adopted a compensatory trunk flexion posture. However, kinematic gait parameters such as walking speed and stride length remained unchanged with the increasing loads. Walking with backpack load of 15%BW and 30%BW resulted in corresponding increase in lumbosacral force of 26.7% and 64% respectively when compared to walking without backpack load.
13	A way of defining the movements imposed on the trunk by carrying.	12 guides of Avignon	A 20 kg load situated at the thoracic level (T9) of the trunk, was placed in a backpack (2.5 kg).	External markers were glued to the projecting contours of the spinous processes of the C7, T7, T12, L3 and S1 vertebrae, the shin and the external occipital tuberosity (EOT). Using a Vicon 140 3-D system we measured the effective mobility of the different spinal	We noticed a significant decrease of the effective inter-segmental mobility (EISM) between S1-L3-T12 ($p < .01$) while backpacking a 22.5 kg load. A decrease of EISM also appeared at the next level between L3-T12-T7 ($p < .05$). An increase of the EISM between T7-C7-EOT was noted ($p < .05$). We supposed that strength loss of the back muscles and/or angular oscillations of the trunk could be a

				segments in the sagittal plane during one step.	common cause of symptoms during backpacking. The subjects using this type of load carrying should adopt an adequate position of the lumbar, dorsal, and cervical vertebrae.
14	Recommendations on backpack loading advice restricting the load to 10% of body weight and carrying the load high on the spine.	20 students	0%-5%-10%-15% of BW	The effects of increasing load and changing the placement of the load on the spine, thoracic vs. lumbar placement, during standing and gait were analysed by studying physiological, biomechanical, and subjective data.	Significant changes were: (1) increased thorax flexion; (2) reduced activity of M. erector spinae vs. increased activation of abdominals; (3) increased heart rate and Borg scores for the heaviest loads. A trend towards increased spinal flexion, reduced pelvic anteversion and rectus abdominis muscle activity was observed for the lumbar placement. The subjective scores indicate a preference for the lumbar placement. These findings suggest that carrying loads of 10% of body weight and above should be avoided, since these loads induce significant changes in electromyography, kinematics, and subjective scores.
15	Evaluate the effects of these non-neutral postures on biomechanical loading and then reconsider the backpack system design recommendations.	15 participants	18.2kg	Participants were asked to support an 18.2 kg load on their back while assuming static forward flexed postures of the torso (15 degrees, 30 degrees, 45 degrees, and 60 degrees of sagittal bend). The mass on the back was attached to the participant through two different harness mechanisms: a basic harness design (as seen on college student backpacks) and a more advanced design containing lateral stiffness rods and a weight-bearing hip belt (as seen on backpacks for hikers). While performing these static, posture maintenance tasks, the activation levels	Results showed that there was a significant interaction between harness type and forward flexion angle for the trapezius and the erector spinae muscles. The normalized EMG for the trapezius muscles showed a 14% and 11% reduction in muscle activity at 15 degrees and 30 degrees, respectively, with the advanced design but these positive effects of the advanced design were not found at the greater flexion angles. Likewise, the erector spinae muscles showed a 24% and 14% reduction in muscle activity at 15 degrees and 30 degrees, respectively, with the advanced design harness but these effects of the advanced design were not found at the greater forward flexion angles. The level of forward

				of the bilateral trapezius, erector spinae, and rectus abdominis were collected	flexion angle affected the rectus abdominis muscle activity, but neither the harness type main effect nor the interaction of harness type and forward flexion angle was significant. The subjective survey results agreed with the EMG results and showed the advanced design harness was generally more comfortable with respect to the shoulder and low back areas.
16	Analyse trunk-lower extremity muscle activities and trunk postural changes during the carriage of different backpacks.	19 males (21+/-3 years)	(1) unloaded standing, (2) 10% body weight (BW) load (in the form of a backpack), (3) 15% BW load and (4) 20% BW load.	Abdominis, erector spinae, vastus medialis and biceps femoris muscle activities were recorded using surface electromyography (SEMG), while trunk inclination, side flexion and rotation were measured by using VICON 250 during all standing modes.	Rectus abdominis muscle activities increased progressively and disproportionably as the backpack load increased. As for the trunk posture, almost the same backward inclination was adapted even with increasing backpack heaviness. Twenty percent BW backpack causes the most significant muscular and postural changes, so it should be avoided.
17	Investigate the effect of different load carriage methods on spinal loading over time via the measurement of spinal compression.	8 male adults	load equivalent to 15% BW	They were asked to carry a load equivalent to 15% of their body weight either anteriorly or posteriorly for 20 min followed by 10 min of unloading. Their statures were measured before load carriage and every 2 min after carrying the load. The sequence of loading conditions was randomized, and the participants took a 20-min rest with Fowler's posture for spinal length recovery prior to each testing condition. The amount of spinal compression was found to be associated with carrying duration.	Spinal compression during anterior carriage was larger than that of posterior carriage. There was a mild recovery of spinal compression after the removal of the carried load for both the anterior and posterior carriage conditions.
18	Investigate the carry-over effects of backpack carriage on	13 healthy adults	with backpack (10% BW)	They were instructed to walk on a treadmill for 30 min with backpack	During backpack carriage, reduction in lumbar lordosis and posterior pelvic tilt with significant

	trunk posture and repositioning ability.			(10% body weight) followed by 30-min unloaded walking. Participant's trunk posture and repositioning ability were measured at different time points.	increased cervical lordosis, thoracic kyphosis and trunk forward lean were observed. There was also a significant increase in repositioning errors in all spinal curvatures and trunk forward lean. After removal of the carrying load, there was a tendency for restoration of trunk posture and repositioning ability. However, the cervical lordosis and the repositioning error of all spinal curvatures could not be fully returned to the levels of the preload condition (all $p < 0.05$). The persistent changes in both spinal curvature and repositioning ability revealed an increased risk of spinal injury even after the backpack was removed, and the effects on the neck and back pain warrant future study.
19	Identify how load-carrying postures and gender affect postural sway	8 males and 8 females	A 10 kg load	The participants were instructed to look straight ahead and stand upright on a force platform as still as possible with feet together. A 10-kg load was carried in three different postures during upright stance: anterior load carriage, lateral load carriage, and posterior load carriage	Experimental findings suggested that lateral load carriage appeared to be more stable than anterior and posterior load carriage, and the females might have higher fall risks than males when carrying external loads. Practical implications and limitations of the study were discussed.
20	Investigate differences in the accelerations placed on males and females whilst carrying different loads when walking.	16 males and 13 females	no weight, 10% and 20% BW added in a backpack.	Accelerometers were attached to the right shank and the centre of the forehead.	Males have lower accelerations than females both in the head ($2.62 \pm 0.43G$ compared to $2.83 \pm 0.47G$) and shank ($1.37 \pm 0.14G$ compared to $1.52 \pm 0.15G$; $p < 0.01$). Accelerations for males and females were consistent throughout each backpack condition ($p > 0.05$). The body acts as a natural shock absorber, reducing the amount of force that transmits through the body between the foot (impact point) and head. Anthropometric and body mass distribution differences between males and females may result in women receiving

					greater impact acceleration compared to men when the same load is carried.
21	Evaluate the effects of important task demands, related to load mass and size, on potential mechanisms linking traditional PLC with LBP. Nine healthy participants completed PLC tasks with three load masses (20%, 35% and 50% of individual body mass) and three load sizes (small, medium and large).	9 healthy persons	20%, 35% and 50% of individual body mass) and three load sizes (small, medium, and large)	Torso kinematics, kinetics, muscle activity and slip risk were evaluated during PLC on a walkway, and torso movement stability was quantified during PLC on a treadmill. Increasing load mass caused increased torso flexion, L5/S1 flexion moment, abdominal muscle activity and torso movement stability in the frontal plane.	Increasing load mass caused increased torso flexion, L5/S1 flexion moment, abdominal muscle activity and torso movement stability in the frontal plane. Increasing load size also caused higher torso flexion, peak torso angular velocity and acceleration, and abdominal muscle activity. Complex interactive effects of load mass and size were found on paraspinal muscle activity and slip risk. Specific task demands, related to load mass and size, may thus influence the risk of LBP during PLC.
22	Explore posture deviation variability caused by load carriages depending on natural posture imbalance to provide information about a carrying habit exaggerating an individual's posture imbalance.	17 females	(a) the anatomical pose (P1) face forward and feet placed at shoulder width without carrying an item, (b) carrying a backpack (P2), (c) carrying a shoulder bag on the right shoulder (P3R) and the left shoulder (P3L), (d) carrying a bag cross-body with a strap placed on the left shoulder to place the weight at the hip level on the right side (P4R) and the strap and handbag placed in the opposite direction (P4L), and (e) carrying a bag with the right hand (P5R) and the left hand (P5L).	They were each scanned wearing their own underwear (bra and panties) in: (a) the anatomical pose (P1) face forward and feet placed at shoulder width without carrying an item, (b) carrying a backpack (P2), (c) carrying a shoulder bag on the right shoulder (P3R) and the left shoulder (P3L), (d) carrying a bag cross-body with a strap placed on the left shoulder to place the weight at the hip level on the right side (P4R) and the strap and handbag placed in the opposite direction (P4L), and (e) carrying a bag with the right hand (P5R) and the left hand (P5L). The bag weight was approximately 10% of a participant's body weight. Five body angles were obtained in each scanning position (eight positions total) for all participants and statistical analyses were conducted for posture assessment.	a) Asymmetrical load positions exhibited greater changes on shoulder and spine posture than a symmetrical load position, exhibiting obvious changes in P3 and P4 rather than P5. (b) The degrees and directions of posture deviation resulting from an asymmetrical load carriage varied depending on those of an individual's natural posture imbalance. When a participant exhibited great posture imbalance in P1, significant differences of posture deviation on the shoulder and spine between R and L positions were observed in P3 and P4. (c) Significant correlations between natural posture imbalance and posture deviation resulting from load carriages were found for most body angles.

			<p>The bag weight was approximately 10% of a participant's body weight</p>	<p>Three statistical test methods were used: (a) Paired t-test to determine posture changes in each loaded position compared to natural posture in P1. (b) Paired t-test to identify differences of the degree of posture changes between right-side load (R) and left-side load (L) positions to determine a posture deviation tendency with asymmetrical load carriages. (c) Bivariate (Pearson) correlation test to examine how natural posture imbalance and posture deviation co-vary.</p>	
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2.2.3 Discussion

Carrying a load of 10% of BW provokes a reduction of trunk forward angle, a load of 15% BW leads to a reduction of cranio-vertebral angle [1]. Carrying a load of 10% of the BW and above provokes changes in electromyography and kinematics [14]. Backpack carriage causes a reduction in lumbar lordosis and posterior pelvic tilt with a significant increase of cervical lordosis, thoracic kyphosis, and trunk forward lean [18].

Forward lean changes linearly with changes in load to maintain the COM to ankle and knee vector orientation. COM vertical trajectory can be maintained by a combination of invariants including lower-limb segment angles and a constant direction of toe-off impulse vector [7].

During walking, there is a significant difference between traditional and backpack in terms of trunk angle and cranio-vertebral angle. With a traditional backpack, there is a decrease of 10 degrees on cranio-vertebral angle with a load of 25% BW. And, with non-traditional one, trunk forward angle 7.5 and cranio-vertebral on about 7 degrees [3]. Backpack shoulder 1-strap or 2 straps cause exertions carrying 15% BW [5]. Walking with a backpack load of 15% and 30% BW resulted in corresponding increase in lumbosacral force of 26.7% and 64% respectively when compared to walking without the backpack [12]. A reduction of intersegmental mobility between S1-L3-T12 and L3-T12-T7 while backpacking a 22.5 kg was found [13]. Measuring the spinal curvature might indicate changes in posture [11]. During load carrying, the curvature of the spine changes in a short period of the time. Trunk and head flexion did not change with fatigue.

Carrying a load on 20 % BW reduce forward angle and increase fatigue, systolic pressure [6] rectus abdominis muscle activity [9,16] and perceived exertion (RPE) and shoulder discomfort [8]. The 20 % BW also resulted in a mean RPE rating of 'fairly light' which increase too hard when carrying 40% of BW [8]. Support 18.2 kg load on back while assuming static forward flexed postures of the torso (15-30-45-60 degree) on sagittal bend creates a reduction of trapezius and erector muscle activity. At 15 and 30 degrees was found a reduction of 14% and 11 % of trapezius muscle activity and 24% and 14% reduction in erector spinae respectively [15].

Recovery of the person with 20 % BW is slower than 10-15% BW [6,17]. 20% BW of unilateral load provoke a lateral bending, hip abduction, and external knee varus moments during stair negotiation [1]. Asymmetric load carriage, 17% BW produce a stature loss an increase of forward (6 degree) and lateral bending of the spine (12 degree) [10]. Asymmetrical load position exhibited greater changes on shoulder and spine posture than a symmetrical load position [2]. The degree and directions of posture deviation depends of the individual's natural imbalance. If the participant has a normal imbalance, present significant difference on posture deviation on the shoulder and spine between right and left shoulder and hip [22]. 13% BW of maximum curvature change of the whole spine represents the global critical load in accordance with the maximum curvature changes of the four spinal regions [5].

Increasing load mass cause increase on torso flexion, L5/S1 flexion moment, abdominal muscle activity and torso movement stability in the frontal plane. Increasing load size also caused higher torso flexion, peak torso angular velocity and acceleration, and abdominal muscle activity [21]. Complex interactive effects of load mass and size are found on paraspinal muscle activity. Specific task demands, relate to load mass and size can influence the risk of low back injuries during posterior load carriage [21-18]. Anthropometry and body mass distribution differ between male and female. Males have a lower acceleration to the shank [20]. Female have higher fall risk than males [19]. A backpack load limit of 30% BW should be recommended for female recreational hikers during prolonged walked [8].

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2.3 Load carriage and posture in military context: a systematic review of the literature

Two databases were used to search for relevant original research articles using the keywords "load carriage and posture". Table 2.3 describes the databases and the keywords that were used. Following removal of all duplicates, articles were subjected to the specific inclusion criteria, these being (a) excluded the civil field; (b) involving human participants carrying an external load; (c) excluded review; (d) excluded the effect of load carrying on metabolic cost.

2.3.1 Method

Database	Search Terms	Filters	Number after inclusion	Number after exclusion
PubMed	load[All Fields] AND carriage[All Fields] AND ("posture"[MeSH Terms] OR "posture"[All Fields]) AND ("military personnel"[MeSH Terms] OR ("military"[All Fields] AND "personnel"[All Fields]) OR "military personnel"[All Fields] OR "soldier"[All Fields])	Civil Review Metabolic	19	12
Web of Science	load[All Fields] AND carriage[All Fields] AND ("posture"[MeSH Terms] OR "posture"[All Fields]) AND ("military personnel"[MeSH Terms] OR ("military"[All Fields] AND "personnel"[All Fields]) OR "military personnel"[All Fields] OR "soldier"[All Fields])	Civil Review Metabolic	8	5

Tab.2.3 Details of literature search: database used, search terms and inclusions filters

2.3.2 Results

From the primary research, a total of 19 and 8 articles were identified based on PubMed and Web of Science respectively. After exclusion criteria, 12 and 5 articles were selected based on PubMed and Web of Science respectively. The two databases had in common 2 articles (Fig.2.2). A total of 15 articles were selected for this review. Table 2.4 shows the methodologies and major findings.

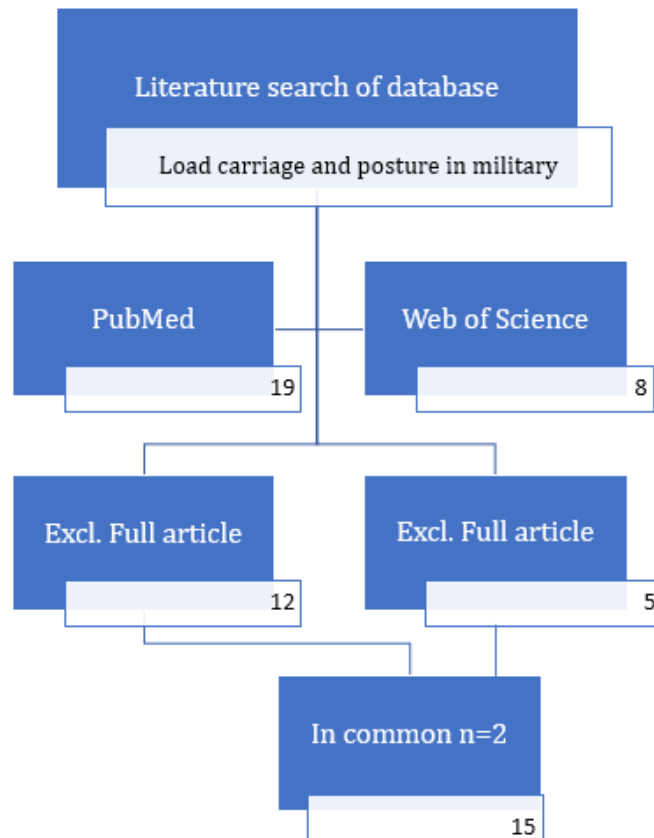


Fig.2.2 A flow chart of the literature review process

Tab.2.4 Summary and critical appraisal of articles included in this review.

Comment: the number of the study is linked with the bibliography.					
Study	Aim	Participants	Load	Task	Findings
1	Investigate the effect of 10% load increment and to find the maximum suitable load for the Malaysian military.	10 soldiers	0% - 40% BW	They participated in an experiment to gather the GRF and kinematic data using Vicon Motion Analysis System, Kistler force plates and thirty-nine body markers. The analysis is conducted in sagittal, medial lateral and anterior posterior planes.	The results show that 10% BW load increment has an effect when heel strike and toe-off for all the three planes analyzed with P-value less than 0.001 at 0.05 significant levels. FDA proves to be one of the best statistical techniques in analyzing the functional data.
2	Examine the extent of loading and resultant strain in the trunk muscles.	37 soldiers	helmet (1.5 kg); load-carrying equipment (1 kg); backpack (15 kg), rifle (3,63 kg)	The trunk posture of soldiers and muscular activity in reaction to different equipment components (helmet, load-carrying equipment, gun, and backpack) were evaluated.	Data indicate that the activity of the trunk muscles examined (latissimus dorsi, trapezius and pectoralis major) is dependent on the weight and distribution of the equipment components. Activity in the trapezius muscle, for instance, was doubled during specific load application. Moreover, the method of carrying the rifle had a significant influence on the activity of the trapezius muscle (one-sided decrease of activity by 50%). Subjects were able to stabilise the body axis in the coronal plane through increased muscle activity. However, in the sagittal plane a compensatory ventral inclination of the body was observed. Uneven load distribution can lead to an irregular strain on the musculoskeletal system.
3	Analyse the extent of muscle activity in the lower extremities caused by carrying specific items of equipment.	37 German Air Force soldiers	15% BW and 30% BW	For this purpose, the activity of selected groups of muscles caused by different items of equipment (helmet, carrying strap, backpack, and rifle) in the upper and lower leg was	The activity of recorded muscles of the lower extremity, that is, the tibialis anterior, peroneus longus, gastrocnemius lateralis, gastrocnemius medialis, rectus femoris, and biceps femoris, was found to depend on the weight of the items of equipment. There was no evidence, however, that

				<p>measured by recording dynamic surface electromyograms. Electrogoniometers were also used to measure the angle of the knee over the entire gait cycle. In addition to measuring muscle activity, the study also aimed to determine out what influence increasing weight load has on the range of motion (ROM) of the knee joint during walking.</p>	<p>items of equipment weighing a maximum of 34% of their carrier's body weight had an effect on the ROM of the knee joint.</p>
4	Kinetic changes in gait during low magnitude military load carriage.	10 healthy males	4.2 and 17.5 kg (6.5-27.2% of mean body weight (BW)) and a control condition of no external load (NL).	<p>They were collected while they walked carrying operational loads and a control condition of no external load (NL). The GRF and impulse components were normalised for BW, and data for each load condition were compared with NL in each side applying one-way analysis of variance followed by Dunnett's post hoc test. Right foot data were compared with corresponding left foot GRF data for all load conditions and NL.</p>	<p>There were significant increases in vertical and anteroposterior GRFs with increase in load. Left and right feet GRF data in corresponding load conditions were significantly different in anteroposterior plane. No significant change was observed in the temporal components of support phase of gait. Changes in impulse parameter were observed in the anteroposterior and vertical planes while carrying load greater than 23 and 16.6% of BW for the right foot and left foot, respectively. Result indicates that smaller magnitudes of loads produced kinetic changes proportional to system weight, similar to heavier loads with the possibility of increased injury risk. Observed smaller asymmetric changes in gait may be considered as postural adjustment due to load. Unique physical characteristics of Indian soldiers and the probable design shortcomings of the existing backpack might have caused significant changes in GRF and peak impulse during smaller load carriage.</p>

5	Examines changes in gait and posture caused by increasing load carriage in military LCS.	20 male soldiers	The four conditions used during this study were control (including rifle, boots and helmet carriage, totalling 8 kg), webbing (weighing 8 kg), backpack (24 kg) and a light antitank weapon (LAW; 10 kg), resulting in an incremental increase in load carried from 8, 16, 40 to 50 kg.	They were evaluated in the sagittal plane using a 3-D motion analysis system.	Results showed spatiotemporal changes were unrelated to angular changes, perhaps a consequence of military training. Knee and femur ranges of motion (control, 21.1 degrees +/- 3.0 and 33.9 degrees +/- 7.1 respectively) increased ($p < 0.05$) with load (LAW, 25.5 degrees +/- 2.3 and 37.8 degrees +/- 1.5 respectively). The trunk flexed significantly further forward, confirming results from previous studies. In addition, the craniovertebral angle decreased ($p < 0.001$) indicating a more forward position of the head with load. It is concluded that the head functions in concert with the trunk to counterbalance load. The higher muscular tensions necessary to sustain these changes have been associated with injury, muscle strain and joint problems.
6	Quantify the effect of operationally relevant loads and distributions on lumbar spine (LS) in a group of active-duty Marines.	12 Marines	unloaded and when carrying 22, 33, and 45kg of load distributed both 50% to 50% and 20% to 80% anteriorly and posteriorly.	Magnetic resonance images of Marines were acquired when standing unloaded and when carrying 22, 33, and 45kg of load distributed both 50% to 50% and 20% to 80% anteriorly and posteriorly. Images were used to measure LS and pelvic postures. Two-way repeated-measures ANOVA and post-hoc tests were used to compare LS posture across load magnitudes and distributions ($\alpha=0.05$).	No changes in LS posture were induced when load was evenly distributed. When load was carried in the 20% to 80% distribution lumbosacral flexion increased as a result of sacral anterior rotation and overall reduced lumbar lordosis. This pattern was greater as load was increased between 22 and 33kg, but did not increase further between 33 and 45kg. We observed that the inferior LS became uniformly less lordotic, independently of load magnitude. However, the superior LS became progressively more lordotic with increasing load magnitude
7	Perform a biomechanics-based assessment of body borne load during the walk-to-run transition and steady-state running because	15 male soldiers	(light, ~6 kg, medium, ~20 kg, and heavy, ~40 kg).	They had trunk and lower limb biomechanics examined during these locomotor tasks	During the walk-to-run transition, the hip decreased ($P = 0.001$) and knee increased ($P = 0.004$) their contribution to joint power with the

	historical research has limited load carriage assessment to prolonged walking.			with three different load configurations.	addition of load. Additionally, greater peak trunk ($P = 0.001$), hip ($P = 0.001$), and knee flexion ($P < 0.001$) moments and trunk flexion ($P < 0.001$) angle, and reduced hip ($P = 0.001$) and knee flexion ($P = 0.001$) posture were evident during the loaded walk-to-run transition. Body borne load had no significant effect ($P > 0.05$) on distribution of lower limb joint power during steady-state running, but increased peak trunk ($P < 0.001$), hip ($P = 0.001$), and knee ($P = 0.001$) flexion moments, and trunk flexion ($P < 0.001$) posture were evident. During the walk-to-run transition the load carrier may move joint power production distally down the kinetic chain and adopt biomechanical profiles to maintain performance of the task. The load carrier, however, may not adopt lower limb kinematic adaptations necessary to shift joint power distribution during steady-state running, despite exhibiting potentially detrimental larger lower limb joint loads. As such, further study appears needed to determine how load carriage impairs maximal locomotor performance.
8	Kinematic analysis of males with transtibial amputation carrying military loads	10 males	Three loads (none, 21.8, and 32.7 kg)	Participants completed six treadmill walking trials in all combinations of two speeds (1.34 and 1.52 m/s).	Persons with TTA exhibited biomechanical compensations to carried loads that are comparable to those observed in uninjured individuals. However, several distinct gait changes appear to be unique to those with TTA, notably, increased dorsiflexion (deformation) of the prosthetic foot/ankle, less stance knee flexion on the prosthetic limb, and altered trunk forward lean/excursion. Such evidence supports the need for future work to assess the risk for overuse injuries with carried loads in this population in

					addition to guiding the development of adaptive prosthetic feet/components to meet the needs of redeployed service members or veterans/civilians in physically demanding occupations.
9	Examine the impact of weight and weight distribution of body armor and load carriage on static body balance and leg muscle function	7 males		A series of human performance tests were conducted with seven male, healthy, right-handed military students in seven garment conditions with varying weight and weight distributions.	Results of this study showed that uneven weight distribution of garment and load beyond an additional 9 kg impaired static body balance as evidenced by increased sway of center of plantar pressure and asymmetry of weight bearing in the feet. Added weight on non-dominant side of the body created greater impediment to static balance. Increased garment weight also elevated peak EMG amplitude in the rectus femoris to maintain body balance and in the medial gastrocnemius to increase propulsive force. Negative impacts on balance and leg muscle function with increased carrying loads, particularly with an uneven weight distribution, should be stressed to soldiers, designers, and sports enthusiasts.
10	Determine how load carriage affects plantar pressure distributions during gait in individuals with varying arch types.	97 men, 18 women	3 loaded conditions (uniform, 20-kg load, and 40-kg load)	They were categorized as having high-, normal-, or low-arched feet on the basis of published cutoff values for the arch height index. Plantar pressure measurements were obtained with the use of an in-shoe pressure measurement system while participants wore combat boots and walked on a treadmill under 3 loaded conditions	A significant interaction existed between arch type and load for MaxF and FTI in the medial midfoot, with greater force in low-arched feet. In the medial forefoot, MaxF and FTI were greatest in high-arched feet across all load conditions. In the great toe region, low-arched and normally arched feet had greater MaxF and FTI. The relative distribution of FTI increased proportionately in all regions of the foot regardless of arch type for all load conditions.

11	To characterize the effect of the load on spinal kinematics of active Marines under typical load carrying conditions from a macroscopic and lumbar-level approach in active-duty US Marines.	10 Marines	Load (L02), after 45 minutes of standing (L03) and walking (L04) with load, and after 45 minutes of side-lying recovery (UN5). Custom-made software was used to measure whole spine angles, intervertebral angles, and regional disc heights (L1-S1). The total was (50.8 kg).	Sagittal T2 magnetic resonance images of the lumbar spine were acquired on a 0.6-T upright magnetic resonance imaging scanner for 10 active-duty Marines. Each Marine was scanned without load (UN1), immediately after donning load (L02), after 45 minutes of standing (L03) and walking (L04) with load, and after 45 minutes of side-lying recovery (UN5). Custom-made software was used to measure whole spine angles, intervertebral angles, and regional disc heights (L1-S1). Repeated measurements analysis of variance and post hoc Sidak tests were used to identify significant differences between tasks ($\alpha = 0.05$).	The position of the spine was significantly ($P < 0.0001$) more horizontal relative to the external reference frame and lordosis was reduced during all tasks with load. Superior levels became more lordotic, whereas inferior levels became more kyphotic. Heavy load induced lumbar spine flexion and only anterior disc and posterior intervertebral disc height changes were observed. All kinematic variables returned to baseline levels after 45 minutes of side-lying recovery.
12	The effect of military load carriage on ground reaction forces.	15 males	Military boot, rifle, webbing 8 and 16 kg, backpack 16 kg and LCS 24, 32 and 40 kg.	Participants completed 8 conditions.	Results showed that load added in 8 kg increments elicited a proportional increase in vertical and anteroposterior ground reaction force (GRF) parameters. Rifle carriage significantly increased the impact peak and mediolateral impulse compared to the boot condition. These effects may be the result of changes to the vertical and horizontal position of the body's centre of mass, caused by the restriction of natural arm swing patterns. Increased GRFs, particularly in the vertical axis,

					have been positively linked to overuse injuries. Therefore, the biomechanical analysis of load carriage is important in aiding our understanding of injuries associated with military load carriage.
13	Investigate the effects of load weight carried by soldiers upon postural sway.	40 male soldiers	the load weight conditions, comprised of Army clothing and load-carriage equipment were 6, 16, and 40 kg.	Postural sway and muscle activity were measured while participants stood on a force plate.	With an increase in load weight, stabilogram-diffusion analysis revealed that random movement of postural sway decreased. Also, with an increase in load weight, center of pressure excursions increased linearly but muscle activity changed minimally. In short, increasing load weight challenged the load carriers' stability, reduced the randomness of postural sway and required the load carriers to exert greater control of the load in order to maintain balance.
14	Evaluate how Modular Lightweight Load-Carrying Equipment (MOLLE) fits women while walking on level surfaces with different loads, to examine women's load carriage performance before and after a simulated march using five load levels, and to examine the relationship between shoulder and leg muscle strength and load carriage performance of women while carrying loads using MOLLE.	5 female soldiers	five levels of load (no load, 20, 30, 40, and 50 pounds corresponding to 9.07, 13.04, 18.14 kg) using MOLLE.	The women carried five levels of load (using MOLLE).	With increased loads, women showed increased double-limb support time, decreased single-limb support time, increased trunk forward inclination excursion, decreased knee excursion, decreased medial-lateral excursion of center of gravity (COG), and increased vertical excursion of COG. Hip abductor strength was a strong predictor of COG vertical excursion. Some women required modification of the padded hip belt to ensure weight distributed evenly around the pelvis.
15	The effect of loads carried on the shoulders.	12 male subjects: 4 hikers, 4 occasional hikers, and 4 novices.	10, 15, and 20 kg	They walked with a frame pack carried by for 30 minutes on a 5% inclined treadmill at 3.6 km/h to simulate moderate hiking. The load was carried at T9 and was increased (10, 15, and 20 kg) after 1, 20, and 25 minutes.	The data from force transducers placed on the shoulder straps were collected for 30 seconds at 100 Hz. Shoulder strain appeared to be the limiting factor in load carriage. The optimal carrying method depends on the person, but it has been shown that decreasing stride length and wearing appropriate footwear reduces the strain on the shoulders.

2.3.3 Discussion

With increasing load weight, center of pressure excursion increases linearly and requires the load carriers to exert greater control to maintain balance [13]. Uneven weight distribution of the garment and load beyond an additional 9 kg impairs static body balance because of the asymmetry of weight distribution on the feet [9] and elicits a proportional increase in vertical and anterior-posterior ground reaction forces [12]. Carrying a load in the 20% to 80% distribution provoked a lumbosacral flexion that creates a sacral anterior rotation reducing the sacral lordosis [6,11]. Heavy load causes lumbar spine flexion [5,11] and intervertebral disc height changes [11]. Contrarily, increasing load magnitude progressively from 22-33-45 kg induces superior lordosis [6]. Uneven load distribution can lead to an irregular strain on the musculoskeletal system. [2]. 10 % BW load increment has significant effect on GRF for a Malaysian military [1].

Side-lying recovery after 45 minutes restores all the kinematic variables to the baseline [11]. Smaller magnitudes of loads produced kinetic changes proportional to system weight [4]. Changes in impulse parameters are observed in the anteroposterior and vertical planes while carrying a load greater than 23 and 16% of BW for the right and left foot respectively [4].

Extremes of arch height and heavy loads carried by military personnel are associated with increased risk for overuse injury. A significant interaction exists between arch type and load for maximal force ($p=0.001$) and force time integral ($p\leq 0.001$). The impact of load carriage on plantar pressure distributions during gait in medial forefoot, in terms of maximal force and force time, are greatest in high arched feet across all load conditions (uniform, 20 kg, 40 kg). In the great toe region, low and normal arched feet demonstrate greater maximal force and force time integral. The relative distribution of force time integral increases proportionately in all regions of the foot regardless of arch type for all load conditions. Force distributions may demonstrate different strategies to generate a rigid lever during toe-off [10].

34% of BW causes an effect on the knee joint [3]. Persons with transtibial amputation have an increased dorsiflexion of the prosthetic foot/ankle, a reduced stance knee flexion on the prosthetic limb and an altered forward lean/excursion [8].

Walking on level surface simulated different load carriages (20,30,40 pounds corresponding to 9.07, 13.04, and 18.14 kg) before and after a simulated march, showed progressively an increase in double limb support time, decreased single limb support time, increased trunk forward inclination excursion, decreased medio-lateral excursion of center of gravity and increased vertical excursion of COG. The hip abductor reveals to be a strong predictor of COG vertical excursion. Decreasing stride length on a backpack and wearing appropriate footwear reduces the strain on the shoulder [15]. During the walk to run transition the load carrier may move joint power production distally down the kinetic chain and adopt a biomechanical profile to maintain performance of the task [7]. Increasing load, women showed increased double-limb support time, increased trunk forward inclination excursion of center of the gravity. Some women required modification of the padded hip belt to ensure weight distributed evenly around the pelvis [14].

The method of carrying a rifle has an influence on the activity of the trapezius muscle (one side decrease of activity by 50%) [2]. Rifle condition exhibited a greater impact peak, maximum propulsive force, and medio-lateral impulse, while decreasing the force minimum compared to the boot condition. The most likely mechanism behind these changes to GRF parameters with rifle carriage is either the restriction of natural arm swing patterns, or the load of the rifle being added to the anterior of the body [12].

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Use of smart clothing. State of the art

3.1 Passing through the fabric: the smart clothing era

Smart clothing or “intelligent textile” represents a new class of wearable textile design systems with interactive technologies, intended to be attractive, comfortable and ‘fit for purpose’ for the identified user.

Passing through the borders (see annex), the electronics, and the textile creating connection between the two, opens new frontiers in the human factor field (Fig. 3.1).

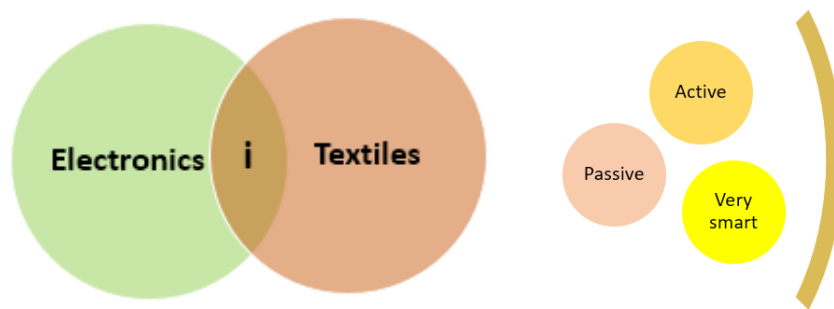


Fig.3.1 Intelligent textile fusion and differentiation

Fibers and filaments yarns together with woven and non-woven structure that feature electronics capable of sensing passively and actively, activate and interact in response to the environmental and the wearer’s conditions and in addition adapts their behavior to the given circumstances are becoming very smart [1-2].

The fabric sensors can detect bioelectric (ECG, EMG, EEG, EOG, ENG), thermal (temperature and the relative surface map), mechanical (movement, contact pressure), optical and chemical signals (sweat composition, inhaled/exhaled air composition, contaminants). They can include active functionality like power generation or storage, assistive technologies, human interfaces elements and radio frequency (RF) categories.

If you consider that your clothes are worn for 24 hours, then the smart cloths are considered the most affordable for monitoring the subject.

The innovative fusion gave us the idea that they appear recently to the public but the history of smart textile goes back over 75 years. Images from a patent of 1942 show concepts developed around the electronics in clothing with the development by Berkey E. Cover [3] of a two-way radio garment or coat and equipment for transmitting and receiving audible signals for use by policemen, sailors, miners, or others working in tunnels or underground (Fig. 3.2).

This is the first smart shirt address to monitor vital signs on a soldier such as heart rate, respiration rate, electrocardiogram, body temperature, and pulse oximetry in an ecological and non-intrusive approach.

Sensing clothing offers the unique opportunity to implement a non-intrusive monitoring for investigating the human physiology [5].

The design research pass through scholarly boarders between semantic, syntactic, and pragmatic dimension of the research [6].

The semantic part can be defined by the context of the end-user identifying the environment. Then the synthetic part takes in care the design process. And finally, the pragmatic part focuses on the end user product.

Smart cloth meets the synthetic or design process defining the design requirements. These are translated into properties that are achieved through material fabrication technologies by applying design parameters.

The requirements are represented by the functionality, the usability, the durability, the shape conformability, the connectivity and the affordability of the smart product.

Also, wearability play an important role into the design. Gemperle et al.[7] defined 13 points as guideline for wearability: the placement of the sensor, the form language (shape), the dynamic structure, the proxemics (human perception of the space), the sizing (for body diversity), the attachment, the containment (considering inside the form), the weight (as it spread across the human body), the accessibility (physical access to the form), the sensor interaction (for passive or active input), the thermal, the aesthetics and finally the long term of use (effect of the body and mind).

Bioelectric signals are acquired through textrode (textile electrodes) that are constituted of electrically conductive yarns that are in contact with the skin. We distinguish metal yarns (stainless steel, copper or silver mixed with natural or synthetic fibers) and yarns containing electro-conductive fibers (polymeric or carbon coated threads). In that case the textrode doesn't required electro conductive gel but sweat (perspiration).

As well, strain gage textile sensors are used to analyse breathing parameters. Mechanically, they elongate in relation to body motion structures.

We can distinguish pressure sensors capable of acquiring gesture recognition, breathing, switch weighting scale and acceleration [1].

Today the smart clothing era is creating a healthcare community capable of encroaching into new territories and compiling a more complete picture of the analysing group, including different geographies or specifics diagnosis, in terms of health and safety.

They are covering different areas of application such as sport, wellness, entertainment and leisure, fashion, space, protection, safety, and military.

Protection, space, safety, and military are the areas where the smart clothing has become the science and technology frontier for the future.

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3.2 A review of smart clothing in the military (*)

(*) Scataglini S., Andreoni G., Gallant J.

“A review of smart clothing in Military”, Proceeding WearSys '15 Proceedings of the 2015 workshop on Wearable Systems and Applications, Poster, Pages 53-54.ACM New York, NY, USA, 2015.

The soldier of the future is most likely going to be the protagonist in the practical application of wearable technology [1]. In fact, the first idea to put embedded sensors into garments was given birth in the military field thanks to Dr. Sundaresan Jayaraman, researcher at the Georgia Institute of Technology. The wearable T-shirt won the best invention of the Millennium (Fall 1998) and TIME named it as one of the best inventions in 2001[2]. Today wearable technologies are evolving not only in sensorized garments but also integrated in small body accessories (bracelets, necklaces, rings). In this paper, we will focus only on sensorized garments applied to space and military applications. At the moment, the experience is very limited. We can recapitulate the goals of these applications in the following points:

- Health monitoring
- Environmental Safety monitoring
- Stress management
- Empowering human functions

3.2.1 Stress Management

One main issue in these users is stress management. Wearable device systems like BioHarness [3], are capable of measuring stress levels of firemen, soldiers and even astronauts.

The European Project ProeTEX (PROtection,ETEXtiles:MicroNanoStructured Fibre Systems for Emergency-Disaster Wear) [4] focused on the development of e-textiles to be used in wearable textile systems for emergency disaster intervention personnel and injured civilians. The international consortium joining forces in this project had 23 partners from 8 different countries consisting of universities, research institutions, industries, and organizations. The wearable system consists of a wearable t-shirt, jacket and also boots. The system enables detection of health status of the subject (heart rate, breathing rate, body temperature, blood oxygen saturation, position, activity and posture), external information (temperature, presence of toxic gases, and heat flux passing through the garments) and an alert. Monitoring the mental stress in Spanish Armed Forces is the aim of the ATREC project (Assessment in Real Time of the Stress in Combatants). A Smart textrode chest-strap system with 6 repositionable textrodes, combined with smart gloves and upper arm straps permits to evaluate physiological stress indicators as: heart and respiration rate, skin galvanic response, environmental and peripheral temperature [5].

Vital signs of astronauts can be tracked from the land to space thanks to the smart t-shirt Astroskin [6].The wearable t-shirt was used in the expedition called XPAntarctick. The crewmembers were monitored for 45 days from the Antarctick to the University Quebec Lab, sharing data via wireless connection with the Canadian Space Agency. The U.S. army has chosen MIT for a \$50 million research centre, with the goal of creating the uniform of the future. Dava Newman, professor of aeronautics and astronautics and engineering systems at MIT, and her colleagues have engineered a “second-skin” spacesuit, BioSuit [7]. An active compression garment that incorporates small, spring like coils that contract in

response to heat. The BioSuit strives to alleviate astronaut musculoskeletal loss for intravehicular activity (IVA) and is manifest to fly to the International Space Station in 2015[8]. Also, Harvard's Wyss Institute was awarded with a DARPA contract to invest in a soft Exosuit, a smart clothing pants that mimics the action of leg muscles and tendons when the soldier walks, providing assistance at the joints of the leg [9]. As well, the TALOS Exosuit (Tactical Assault Light Operator Suit) [10] involves in the US, 56 corporations, 16 governments agencies, 13 universities, and 10 national laboratories. The suit includes: embedded sensors for monitoring body temperature, heart rate, hydration levels and body position; heaters and coolers to regulate the temperature inside the suit; full-body bulletproof armor; 360 degrees cameras with built-in night vision and a powered exoskeleton. It is expected to be ready by 2018.

3.2.2. Energy production in smart clothing

In terms of energy, Katherine Bourzac, [11] stated that researchers at Princeton University have created a square of flexible silicone material, embedded with a ribbon of a piezoelectric material called PZT, that generates a voltage that can be used to produce electrical current. This can be converted back into mechanical movement. The research program of HFM 132 [12] made a review of combat casualty care, remarking the importance of monitoring vital parameters in soldiers and durability of the device, sometimes up to only 5 min, with a result of inefficiency. This is not the case for other systems like the Comftech t-shirt, that monitors a sky-running race [13]. Solar energy could help us. The U.S. Army's Communications, Electronics Research, Development and Engineering Center (CERDEC) is developing a wearable solar panel that can be integrated in the uniform [14]. As well, a start-up called PowerWalk M-series [15] developed a bionic power product composed of a knee brace. With a device on each leg the walking soldier generated an average of 12 watts of electricity.

3.2.3 Health Status Monitoring

In the concept of prevention and alert, William J. Tharion, monitored 27 soldiers with the WPSM system (Warfighter Physiological Status Monitoring) [16]. This system consists of: a Vital Sign Detection System (VSIDS) which measures heart rate, respiration rate, body motion and body position; a fluid intake monitor (FIM); a sleep watch that estimates sleep through actigraphy; a skin temperature patch and a health hub that hosts the WPSM sensor network and algorithms such as determining life sign status or estimation of thermal injury to the Soldier. Ashok Kumar [17], with a project funded by Defence Research Organization (DRDO), developed a novel uniform referred to as Teleintimation Garment. The goal of the project is to develop a garment to monitor vital parameters and bullet penetration in soldiers and analyse the data through a software, named Soldier's Status monitor, to alert the military unit. To monitor the health status of soldiers (Oxygen saturation, temperature, acceleration, EEG, EKG, Heart rate and blood flow), Hock Beng Lim et al. [18] created an advanced helmet where they integrate a Body Sensor Network embedded within a neck pad, headband, and chin-neck pad. At the university of Buffalo, Prof. Titus [19] also developed electrodes, attached to the skin like a band, that relay information (vital signs, brain activity and heart rate) to a sensor that will deliver information to a remote computer network fuse with Sentient's Digital Clone Live software, validated by NASA. The software analyses data and creates personalized health alerts to the soldier and if necessary, emergency medical facilities in the field. For the

identification of friendly soldiers in action (IFF), the Institute for Soldier Nanotechnologies (ISN) of MIT is working towards weaving fibre-optics, that hold a signal that could be identified through a laser. When shined upon the uniform, it would transmit a friendly signal to the user's own uniform, identifying the suspected soldier as friendly. The absence of a return signal would instantly identify opposition [20].

Researchers at the U.S. Army Natick Soldier Research, Development and Engineering Centre, which develops field and combat clothing, chem-bio protection, body-armour systems, gloves, hats and helmet covers, are now experimenting, making garments with new textiles and 3D printing [21].

The Defense Department's National Center for Telehealth and Technology, for example, offers a mobile App, called BioZen, that can provide sophisticated biofeedback on heart rate, respiratory rate, skin temperature and other factors, though it requires the user to buy compatible medical sensors separately [22]. Carvalho [23] suggested 2025 as a possible date by which soldiers could be using body sensors reported in literature findings and here summarized.

In conclusion, this section summarizes the main smart clothing applications developed in the last decade in the military field. Now, the experience is very limited. In terms of monitoring the soldiers through a t-shirt, different systems exist on the market. The U.S. Army, in the collaboration with MIT, is investing to create the uniform of the future. For the moment, such a smart clothing uniform is not available on the market. The USA Army Natick Soldier research center is searching to make garments with new textiles and 3D printers. New applications and materials have been developed with the aim to have devices that can monitor the subjects for longer time and harvest self-energy or solar energy. The next step will be the integration of the existing wearable technologies in usable smart clothing and bring them from the lab to the field.

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Design of smart military equipment and the relative monitoring

4.1 Rationale of the study

The soldier is like a high-performance athlete, but he/she performs at a lower physical level for an extended period and career. The physical efforts of the tactical athlete cannot be picked out or periodized like for sports athletes. The prediction of events is highly uncertain in the military context. Musculoskeletal injuries are the leading cause for the medical profile during training and military operations. Big efforts are made in the screening and prediction of these kinds of injuries.

It is very clear that the multifactorial ground of these injuries makes them hard to predict. The performance and underperformance of a tactical athlete do not solely depend on physical factors but also on mental fitness, nutrition, rest & recovery and so on. The (re)occurrence of musculoskeletal injuries follows the same path.

Smart clothing technology can allow to collect a lot of data on the physical load on the tactical athlete, the physiological response to it, the behavior of the individual, etc.

Smart clothing can enable the military rehabilitation specialist to monitor performance of the patients defining a specific protocol based on algorithms and an end-user interface adapted to the purpose of the user's needs.

Body-worn health monitoring systems measure physiological signals in real time to track individuals' physical condition and performance in an ecological approach. Combining data from established human monitoring technology with environmental and performance information, provides detailed live feedback from military rehabilitation training, monitors their well-being and records changes in ability over time.

Taking this into account, we designed a smart cloth aims to monitor human performance and health in soldier.

4.1.1 Research pathway

The overall S&T objectives of this research were:

- Definition of the user requirements and user needs based on the evaluation of the literature and measurement chain of the user.
- The design and selection of adequate breathable fabrics that combined can preserve comfort and fitting of the garment where it is needed.
- The integration of the sensing technology into the garment.

- 3D printing techniques and materials to design a waterproof electronics package enabling to monitor the wearer's performance also in the water in real time.
- The study of biometric measurements, algorithm detection and training protocols.

4.1.2 Research goal

This technology enables the military rehabilitation specialist to monitor performance of the patients defining specific protocols based on algorithms and end-user interface adapted to the user's needs.

Body-worn health monitoring systems measure physiological signals in real time to track individuals' physical condition and performance.

Combining data from established human monitoring technology with environmental and performance information, provides detailed live feedback from military rehabilitation training, monitors their well-being and records changes in ability over time.

The long-term concept is to provide a common wearable biomedical sensor system that extends from training and operational performance monitoring enabling Defense to improve military performance guarding the health and security of its personnel.

The smart technology equipment is composed by:

- A wearable device (waterproof package) measuring and recording motion data (3D accelerations) and physiological data (heart rate variability).
- A smart shirt (long sleeves) with two textrodes embedded into the cloth. The new shirt presents a hidden pocket inserted on the right shoulder. This gives the possibility to transform the shirt by inserting a pad of D30 material for shock absorption and impact protection during activities like shooting.
- A smart vest with two textrodes embedded into the cloth.
- A mobile app for real time processing and visualization in real time.

4.2 Design of smart clothing for Belgian soldiers through a preliminary anthropometric approach (*)

(*) Scataglini S, Andreoni G., Truyen E., Gallant J., VanTiggelen D.

“Design of smart clothing for Belgian soldiers through a preliminary anthropometric approach”, Proceedings 4th DHM Digital Human Modeling, Montréal, Québec, Canada, 15-17 June 2016.

4.2.1 Introduction

Smart clothing or “intelligent textile” represents the new class of wearable textile design era 2.0 with interactive technologies, intended to be attractive, comfortable and ‘fit for purpose’ for the identified user. The fields of applications are very different such as healthcare, fitness, sport [1], lifestyle, space exploration, public safety, and military [2]. The first idea to embed sensors into the garments in the military field was by researchers of the Georgia Institute of Technology on a US Defense Advanced Research Project Agency grant [3]. The main goal was to monitor the status of the soldier and to reveal eventual injuries and their influence on his/her health. Scataglini et al. [4] recently classified the current main applications of smart clothing in military field in health monitoring, environmental safety monitoring, stress management and empowering human function. Sensing clothing offers the unique opportunity to implement a non-intrusive monitoring, i.e. they represent an extraordinary tool for observing and analysing the complex Human-Machine-Environment system in specific tasks (Fig.4.1).

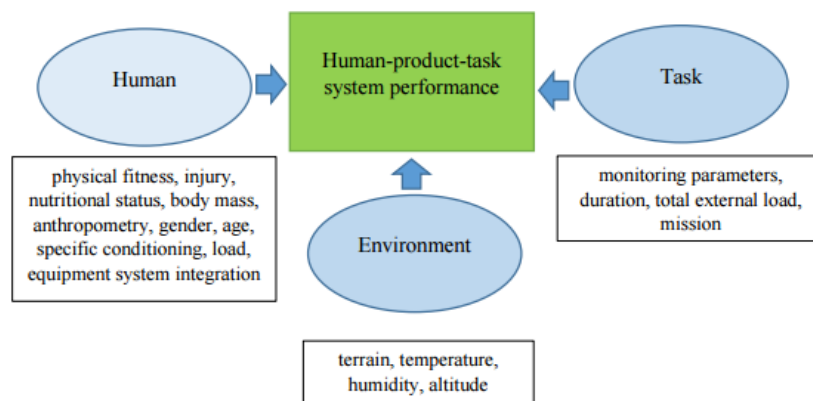


Fig.4.1 Human-product-task system performance and the main parameters to be monitored specifically in the military applications.

The main requirements that a smart clothing is called to achieve are functionality, usability, monitoring duration, wearability, maintainability and connectivity [5], but comfort is another key and transversal factor (also among the previous features) to be considered. The impact of comfort on wearable monitoring technologies has been recognized as an important aspect of its design. Wearing an uncomfortable system compromises the soldier's ability to do his/her job [6]. The functional design process, as well as the knowledge and intuition about the body interface gained from the study of functional design methodologies can help to broaden the scope of interdisciplinary

variables considered in the design of wearable technology, and thereby produce a more successful design. The design process should begin through a deep the anthropometric data retrieval and analysis of the user, and the identification of the user's needs. Anthropometry, or measurement of the body, is a key of the clothing design and the placement of smart textiles around the body. Volume, shape, weight, and adherence to the body of wearable devices must be designed to not affect or interfere with natural movements. Design must also consider the wearability in situation-specific movements required for the accomplishment of a task. In more extreme situations, where weight is a crucial factor as well as volume, stationary or dynamic balance should be preserved and not modified.

Finally, but not exhaustively, other architectural requirements are the connectivity between the textile sensor/component and the electronic part and the connectivity towards the external world.

Once these design criteria have been established, the initial aesthetic design is created within the framework of the user's needs.

The purpose of this paper is to present the methodological approach and the definition of requirements and specifications for the design of smart clothing for military applications, using Belgian soldiers as case study.

4.2.2 Materials and Methods

Wearables have a close, even intimate, relation with the human body. This relation is physical, physiological, and functional. For this reason, the design of "intelligent" garments involve two different macro areas: design issues and technological issues (Fig.4.2). The first one comprehends specifically physical and design related factors such as anthropometry, gender issues, body positions, wearability, elasticity and adherence of the body fixing element or of the garments. The technological issues comprehend the requirements related to the technology as sensing and processing, data transmission and power supply [7].

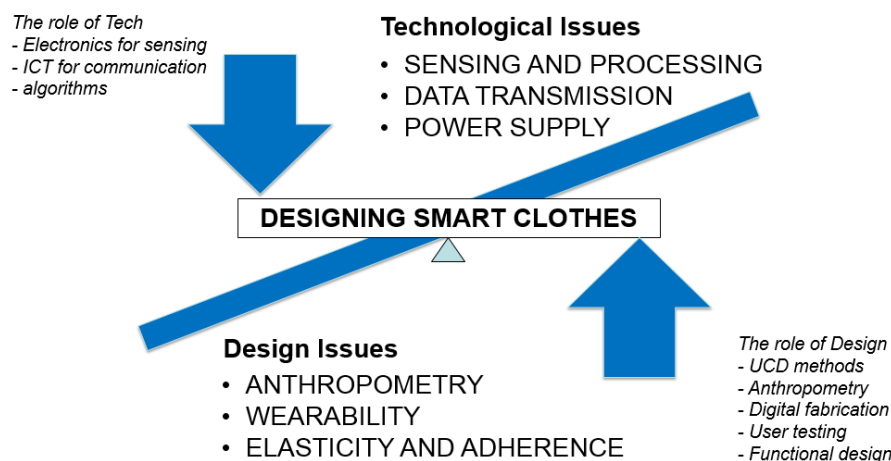


Fig.4.2 The two macroareas of the design process

4.2.2.1 Anthropometric data

The military hospital has a database called “Total Health” where the anthropometric data of the Belgian soldiers are stored. In the database, it is possible to filter anthropometric data considering also the category of affiliation. A total of 1615 male subjects aged between 18 and 35 were recruited and measured according to their proper operational category (they are classified into “Cat Ops A”). For each subject, the stature or standing height, the sitting height, the mass, and the age were recorded. The following Table 4.1 and 4.2 show the main statistics of these data.

	Mean±SD
Height	178.8±0.8
Sitting height	91.55±0.63

Tab.4.1 Stature and sitting height of the studied participants expressed in cm

	Mean±SD
Mass	79.3±18.7
Age	28.44±1.13

Tab.4.2 Mass (kg) and age (years) of the studied participants

From the values of mass and height of the individual, the BMI (body mass index) is computed to have a general representation of the human phenotype. The BMI is an attempt to quantify the amount of tissue mass (muscle, fat, and bone) in an individual, and then categorize that person as underweight, normal weight, overweight, or obese based on that value. Commonly accepted BMI ranges are underweight: under 18.5, normal weight: 18.5 to 25, overweight: 25 to 30, obese: over 30 (Tab 4.3).

BMI	24.8±0.35
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Tab.4.3 Body mass index (kg/m²)

The Belgian soldier has a normal BMI and the related standard deviation is really reduced in value so demonstrating a small inter-subject variability.

4.2.2.2 Anthropometric data extrapolation

To obtain the dimensions of the segment lengths of the average Belgian soldiers, we used Drillis and Contini tables [8] that express the segment length as a fraction of body height, (H). Especially we were focusing to the upper body part. Starting from the shoulder, the chest, the waist, and long sleeve segments measurements expressed as a proportion of the body height we can calculate the segment dimensions and design the shirt model (Fig. 4.3).

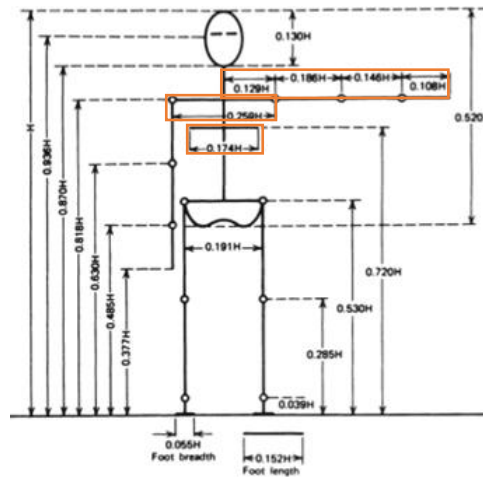


Fig.4.3: Body segment lengths expressed as proportion of body height (H) by Drillis and Contini and the identification of body segment lengths related to the thorax (marked in red) expressed as proportion of body height (H)

4.2.2.3 Experimental design body position and wearability

Designing smart clothes requires as first task the identification of measuring parameter requirements, whose first need is determining sensor placement onto the body and their wearability. For sensor positioning, according to [9], we need to consider areas that are relatively the same size across adults, areas that are larger as surface areas and finally areas that have low movements (Fig. 4.4).

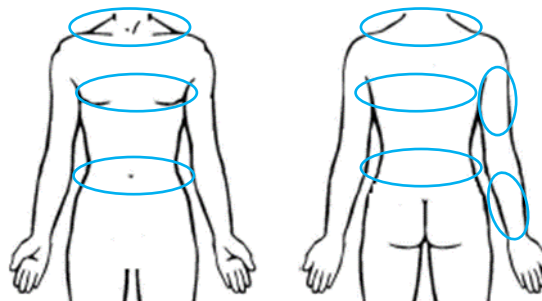


Fig.4.4 Areas of the upper body parts for the sensor placement according with Gemperle et al. (1998) criteria

Considering the Belgian soldier equipment, we eliminated the neck areas and the arms areas. We chose the chest areas due to the equipment interaction and the shooting movements (Fig. 4.5). Timmermans et al. [10] concluded that intervertebral distances in the thoracic spine are different for healthy individuals with different trunk length and different body length.

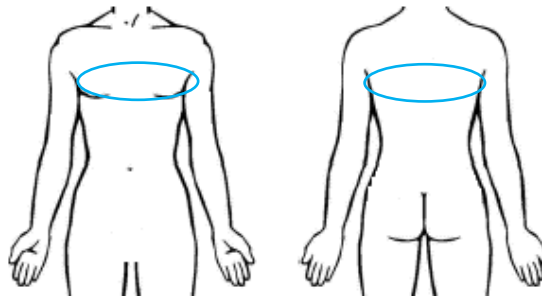


Fig.4.5 Areas of the upper body parts for the sensor placement of our smart shirt as an unobtrusive placement

Elasticity also plays an important role permitting a close contact between the electrodes and the skin. Elasticity is obtained by the design impose criteria that preserve confort and wearability of the smart clothes. High stretch fabrics provide mobility, tight-fitting and enhanced performance. At the same time the adherence should not to be invasive for posture and movements or create a thermal discomfort. According to these criteria the smart shirt was designed with stretch fabrics and cut close to the body for enhanced performance.

4.2.2.4 Technological issues

The first generation of the wearable device technology 1.0 [11] that is based on passive textile has been updated by a technology called wearable 2.0. generation that presents a new textile called interactive textile (i-textile). The new generation provides an integration of the electronic elements into the fabric structures. The smart shirt based on the wearable 2.0. is intended for monitoring the heart rate activity (ECG) and the body acceleration. The base fabric made from textile fibers (polyamide and elastane) is accompanied of textrodes embedded into the clothes. The main advantage of using the textrode is the non invasivity in term of skin irritation for long monitoring due to the unnecessary use of the electrogel. However, the disadvantage can be a poor skin/electrode contact that can be resolved by the insertion of a small sponge under the sensing surface. The choice of the sensing material determines the usability, the durability, maintainability, and the manufacturability of the products. In relation to the maintainability, the smart shirt is washable maintaining the washable capability for several washings (>50). In relation to the usability, functionality and connectively, the smart shirt use steel nickel free snap buttons to provide a stable connection between the electronics part and the textile/component sensor. The electrode (textrode) configuration for heart electrical activity monitoring with the two textrode place respectively on the left and right side of the chest in correspondance with the 10th rib with a mutual distance of 15 cm. A single bipolar derivation was used to record the ECG signal. This setting was intended for measuring only the heart rate (HR) without taking in consideration other ECG physio-pathological features. Regarding the electronic part, an actigraph based on a commercial system was used (PROTHEO I, SXT - Sistemi per la Telemedicina, Lecco, Italy). This monitoring device contains a 3D acceleration sensor (MicroElectroMechanical System, LIS3L06AL, STMicroelectronics, Geneva, Switzerland) a Bluetooth transmission module and a rechargeable Li-ion battery [12]. The wearable device is supported by a mobile app designed for collecting and managing data in real time. The device can acquire the Anterior-Posterior (AP), Medio -Lateral (ML) and Vertical (V) accelerations and the ECG potential.

4.2.3 Results and Discussion

Starting from an anthropometric approach, we defined the mean \pm SD anthropometric data related to a population of 1615 male Belgian soldier between 18 and 30 years.

Through Drillis and Contini table [8] we are able to calculate the segments of the upper body part. These dimensions allow defining the size of the smart shirt.

The next step was to evaluate the sensor body placement, the wearability and textile criteria of the smart cloth.

Different body position sensor placement was evaluated according with [9]. The chest position was chosen as ideal position since it respects the unobtrusive placement.

The technical fit smart shirt, cut close to the body is made of base fabric (polyamide and elastane) and has two textrodes positioned on the 10th rib at the distance of 15 cm between each other. The adherence of the smart shirt allows the wearability of the subject without limiting the movement and the relative performance. The smart shirt is also washable.

Data connection between the textile/component is facilitated by snap buttons (nickel free material). The smart cloth can monitor the ECG value (one single lead) and the body movements (triaxial accelerometer). Bluetooth is used for the real-time communication with a mobile app suited for the purpose. The information can either be stored or immediately transferred to a nearby computer for the analysis.

The smart shirt capabilities allow potentially monitoring the soldier's performance in terms of training, injuries, and psychological status monitoring.

In the future, textile component combination can be introduced on other parts of the equipment adding other sensors functionalities.

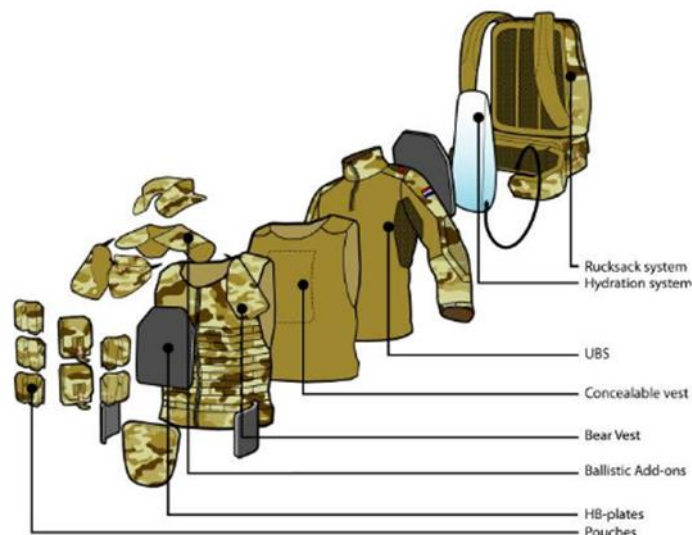


Fig.4.6 Belgian military upper body equipment

4.2.4 Conclusion

This chapter describes the main criteria chosen to design the smart shirt for the Belgian soldier. Anthropometric average soldier dimensions can be used to design ergonomic military tools, equipment [13], (Fig.4.6) and in our purpose the smart shirt.

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4.3 Smart clothing design issues

Based on:

(*)Scataglini S., Truyen E., Perego P., Gallant J., Van Tiggelen D., Andreoni G.

Smart Clothing for Human Performance Evaluation: Biomechanics and Design Concepts Evolution 5th International Digital Human Modeling Symposium, 2017.

4.3.1 Introduction

Stress, training, fatigue, and environmental conditions have a great influence on human-machine-environmental system performance. Combining data from the different components of the system is mandatory. Smart clothing technology together with environmental and performance data provides a detailed live feedback from the soldier's monitoring their physical functions and recording change in ability over time.

The design of smart cloth is crucial to obtain the best results. Identifying all the steps involved in functional design clothing workflow can prevent a decrease in wearer's performance ensuring a more successful design.

Smart cloth represents a "second skin" that has a close, "intimate" relation with the human body. The relation is physiological, psychological, biomechanical and ergonomical.

Effectiveness of functional wear is based on the integration of all these considerations into the design of a smart clothing system.

The design process begins with the analysis of the anticipated user and the identification of the end-user needs. Design and technological issues are the two main macro areas involved in the process together with the esthetical one.

Once these criteria have been established, the initial esthetic design is created within the framework of the user's needs. Design decisions are evaluated and re-evaluated based on physiological, ergonomical and biomechanical monitoring of the wearer's performance. Therefore, alternative solutions are generated for each decision. These alternatives are then evaluated on a weighted scale, to arrive at the best solution or combination of solutions for each decision.

Iterative co-design steps are used to influence the modifications made in the next prototype, and the design process begins again. This ensures that corrections have been made before the design is finalized.

When resources permit, multiple designs will be compared with each other in order to examine the strengths and weaknesses of each.

This chapter presents all the steps involved in the workflow for the design of our smart t-shirt for monitoring soldier's performance.

The PhD project aims at developing smart clothing for monitoring the Belgian soldier taking into consideration in the human centred process the five stages of the design thinking (Fig.4.7).



Fig.4.7 The five stages of the design thinking

4.3.2 Empathising

Empathising is a step to understand the user's needs involved. This step consisted in the observation of the user in the context and the investigation of the user by questionnaire. The observation of the upper body soldier equipment (such as the rucksack, vest and helmet combined with motor task (jumping, climbing, shooting, running)) gave the idea of the first constraints and requirements in the design of smart garment for soldier (Fig. 4.6).

The smart cloth was designed to be used as underwear garment. This means that adding equipment on it should not create interference with the sensing technology embedded in the cloth. Rucksack strap position should be tested in the ideate steps as while impact protection and weapon interactions.

Questionnaire:

Please rate the following variables on a scale. From 1-5 as to the importance they play in your perception of comfort and use.

5 very important

4 of some importance

3 of moderate importance

2 of little importance

1 of no importance

Place a number from 1 to 5 that indicates the rating you would give that variable.

1. Ease of movement
2. Texture
3. Weight of the fabric
4. Color
5. Fit
6. Thermal
7. Care of the garment
8. Self-confidence in appearance
9. Transmission and data storage
10. Easy to clean
11. Functionality and reliability
12. Ease of use
13. Proxemics (as human perception in space)
14. Use for sport activity
15. Use for military training
16. Do you like the idea to have it as military equipment? If the answer is yes, do you have any suggestions?

Question	Subj 1	Subj 2	Subj3	Subj 4	Subj 5	Subj 6
1.	4	5	5	5	5	5
2.	3	3	5	4	4	4
3.	5	4	5	2	2	4
4.	1	1	4	1	3	2
5.	5	4	5	5	3	4
6.	5	2	2	3	4	4
7.	3	3	4	3	3	3
8.	4	2	3	3	3	3
9.	1	4	5	4	5	4
10.	2	3	4	4	3	5
11.	5	5	5	4	3	5
12.	5	4	5	4	3	5
13.	4	4	3	5	2	4
14.	4	4	5	4	2	4
15.	4	4	5	5	4	4
16.	5	5	5	5	5	4

Tab.4.4 Questionnaire results-table

The questionnaire submitted to six soldiers of the Royal Military Academy (Tab.4.4 and Fig.4.8) was helpful to confirm some restrictions, findings and finally the soldier's needs.

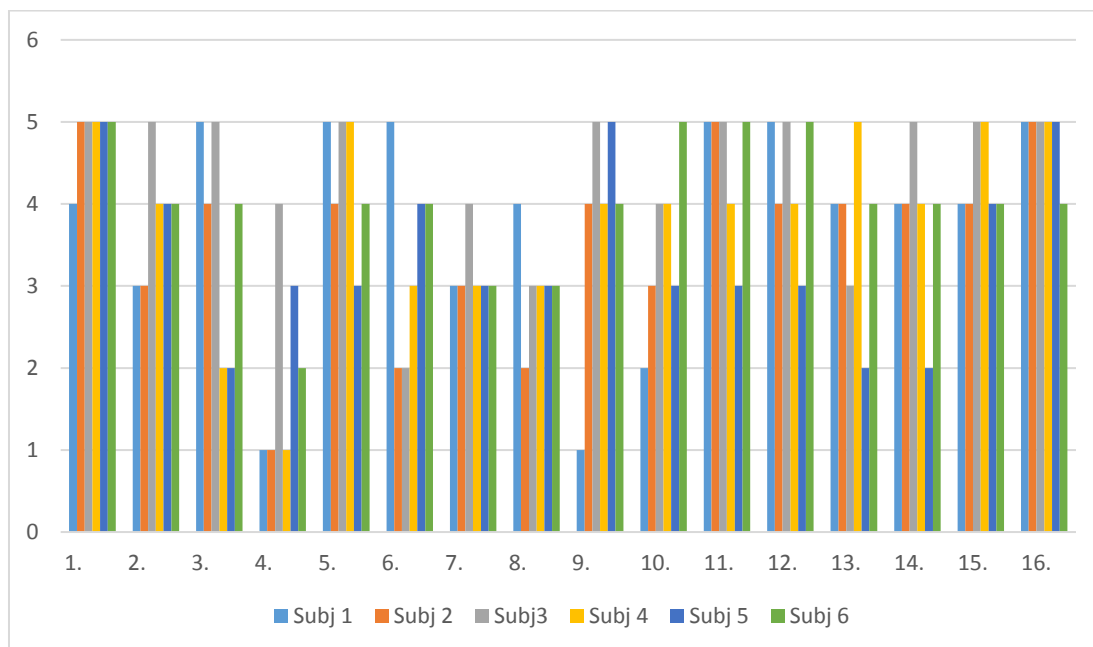


Fig.4.8 Questionnaire results-graph

4.3.3 Defining

The empathy step highlighted that the smart clothing should be addressed to the soldier in military training and can be included as part of the military equipment.

In fact, the soldier is like a high-performance athlete but he/she must perform at a lower physical level for an extended period and career. The physical efforts of the tactical athlete can't be picked out or periodized like for sports athletes. The prediction of events is highly uncertain in the military context. Musculoskeletal injuries are the leading cause for the medical profile during training and military operations. Big efforts are made in the screening and prediction of these kinds of injuries. It is very clear that the multifactorial ground of these injuries makes them hard to predict. The performance and underperformance of a tactical athlete do not solely depend on physical factors but also on mental fitness, nutrition, rest & recovery and so on. The (re)occurrence of musculoskeletal injuries follows the same path. Smart technology can allow to collect a lot of data on the physical load on the tactical athlete, the physiological response to it, the behavior of the individual, etc....

4.3.4 Ideating

After, we understood the users and their needs in the empathise stage, and we analysed and synthesised the observations in the define stage as product requirements. After that, the product requirements were translated in design requirements for the functional design cloth.

The smart t-shirt should be fit, lightweight and breathable allowing freedom of the movement. Additionally, as a technological issue, data storage and transmission, signal reliability and power supply are required for the functionality of the end-user product.



Fig.4.9 The smart shirt

The smart shirt (Fig.4.9) based on the wearable 2.0. is intended for monitoring the heart rate activity (ECG) and the body acceleration. The base fabric is complemented with textrodes embedded into the clothes and positioned on the 10th rib (Fig.4.10). The main

advantage of using the textrode is the non invasivity in terms of skin irritation for long monitoring due to the unnecessary use of the electrogel.
Data connection between the textile/component is facilitated by snap buttons (nickel free material).



Fig.4.10 The textrode area

Regarding the electronic part, an actigraph based on a commercial system was used (POLIMI). This monitoring device contains a 3D acceleration sensor (Freescale MMA7361L) a Bluetooth transmission module (BTM182), a rechargeable Li-ion battery (600 mAh), a SD card for data storage and a microcontroller (ATMEL ATmega328p). The battery can be charged by electromagnetic induction through a TDK (WR-383250-17M2-G) coil. The autonomy is around eight hours with two hours for the charging. A green LED on the top of the device is responsible to communicate the status:

-if the device is blinking two times per second this means that the device is connected in streaming

-if is blinking once each three second it is recording.

- if the LED is lightening is on stand-by modality.

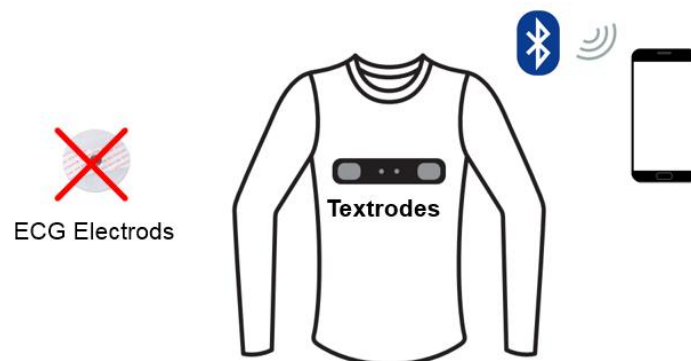


Fig.4.11 The smart system

The device is supported by a mobile app designed at POLIMI for collecting and managing data related to 3D accelerations (Anterior-Posterior, Medio-Lateral and Vertical) and the ECG potential in real time.

4.3.5 Prototyping

The design and the prototyping step was done at POLIMI (Lab Moda).

Starting from an anthropometric approach collected on 1615 soldiers previous presented in chapter 4.1 three prototypes were presented. The first two are presented in this section. The third prototype is discussed in section 4.3.7.

Iterative co-design steps (Fig.4.12) were used to influence the modifications made from the first prototype, and the design process began again.

This ensured that corrections had been made before the design was finalized.

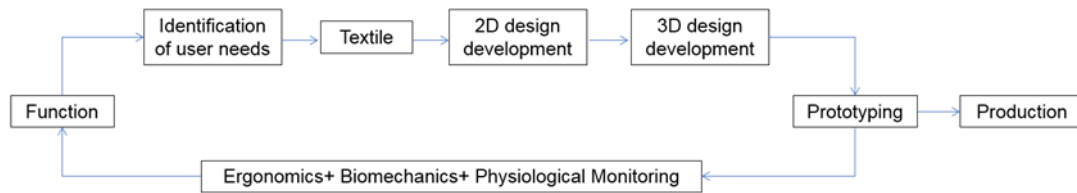


Fig.4.12 Garment co-design workflow

4.3.5.1 First Prototype

The first prototype was draft taking in consideration the body mapping of sweating in male athletics (Smith et al., 2011), Fig.4.12.

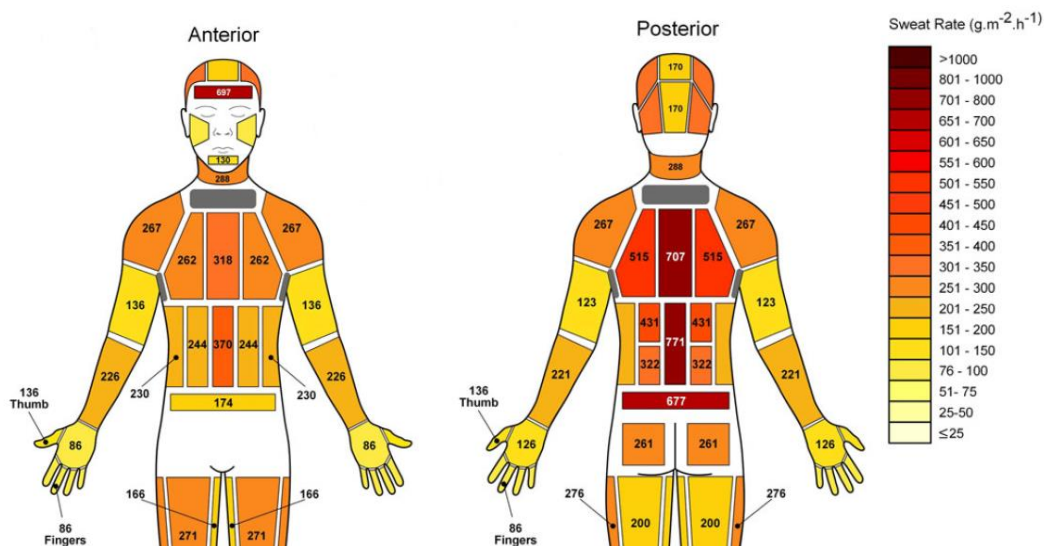


Fig.4.13 Body mapping of sweating in male athletes

Three different textiles were combined in order to respect the sweat rate of the subject:

1) the first (80% Microfibre PA/20% EA(LYCRA®), linear mass density 230g/m²) was used as a principle structure in the areas with a low sweating rate because of the reduced elongation.

Despite the high number of grams per meter it is 50% thinner than any other LYCRA® of similar mass density. This make it also breathable but less than the other.

2) the second textile (72% Microfibre PA/28%EA (LYCRA®), 164g/m²) was used in more sweating rate areas and where more freedom and elongation was necessary.

Regarding the performance both materials have honeycomb construction allowing air circulation between the fibers.

Normally, at that phase technical and clothing experts meets for evaluating the functional design process that integrates embedded sensors into the cloth. To have a qualitative and numerical evaluation our team decided to choose different types of fabrics for introduce the electrodes area.

Three different textiles have been chosen for these experiments:

-a first textile (72%Microfibre PA/28%EA(LYCRA®), 164g/m²)

-a second textile bonded (72%Microfibre PA/28%EA(LYCRA®), 328g/m²)

-a third textile bonded (72%Microfibre PA/28%EA(LYCRA®), 370g/m²).

With every textile a belt of 8 cm width was created and was introduced at chest level for the electrodes placement. Due to the body positioning decision, the textile needed to be fix adherent and at the same time needed to be elastic and rigid combined. At the middle of each belt two snap buttons were created to attach the sensing device technology.

Three different belts were tested joining with adhesive technique at the middle of the first prototyping. Three different monitoring of the subjects in standing demonstrate the wearability and the reliability of the garment. The belt with less mass density was rejected due to the stretch and flexibility that provoked an instability of the sensing device to the chest causing an artifact of the signal movement.

The second textile, bonded solved this problem by blocking the movement of the artifact thanks to the adherence to the chest and the vertical stiffness of the fiber (Fig.4.14).

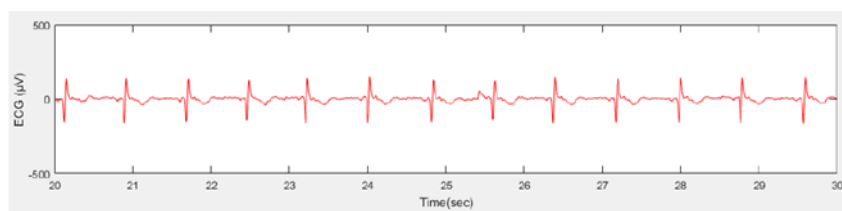


Fig.4.14 ECG signal from the second textiles ((72% Microfibre PA/28%EA LYCRA®), 328g/m²))

Between the second and the third was only the mass density of the textile. Therefore, the second was chosen because it enables more breathability on the chest.

3)the third one is represented by a red belt bonded textile (72%Microfibre PA/28%EA(LYCRA®), 328g/m²) that contains the sensing technology. (Fig.4.15-4.16).

The choice is based on the functional study.

Once the technical and esthetical details of the cut and the proportion of the initial garment prototypes have been fitted, the next step was the introduction of smart technology into the garment.

Bonding technique with adhesive tape was used to join the fabric together creating the 3D shell fabric (Fig.4.15).



Fig.4.15 The first prototype-front



Fig.4.16 The first prototype-back



Fig.4.17 Bonding techniques to create the 3D shell

4.3.5.2 Second Prototype

The second draft involves another concept where a two textile composes the smart garment (Fig.4.18):

- 1) (72% Microfibre PA/28%EA(LYCRA®), 164g/m²)
- 2) a blue belt ((72%Microfibre PA/28%EA(LYCRA®), 370g/m²)) for the sensing technology.



Fig.4.18 The second prototype

This shirt has already a breathable fabric (72% Microfibre PA/28% EA (LYCRA®), 164g/m²) lighter than the other. It requires a rigid structure on the chest to block the elasticity of the fiber in order to maintain the electrodes adherence to the skin as well as the sensing technology stable to the chest. For this was chosen (72%Microfibre PA/28%EA(LYCRA®), 370g/m²).

This concept aims at reducing the number of patterns and consequently the number of joins of the fabrics permitting more comfort and flexibility (Fig.4.19-4.20).

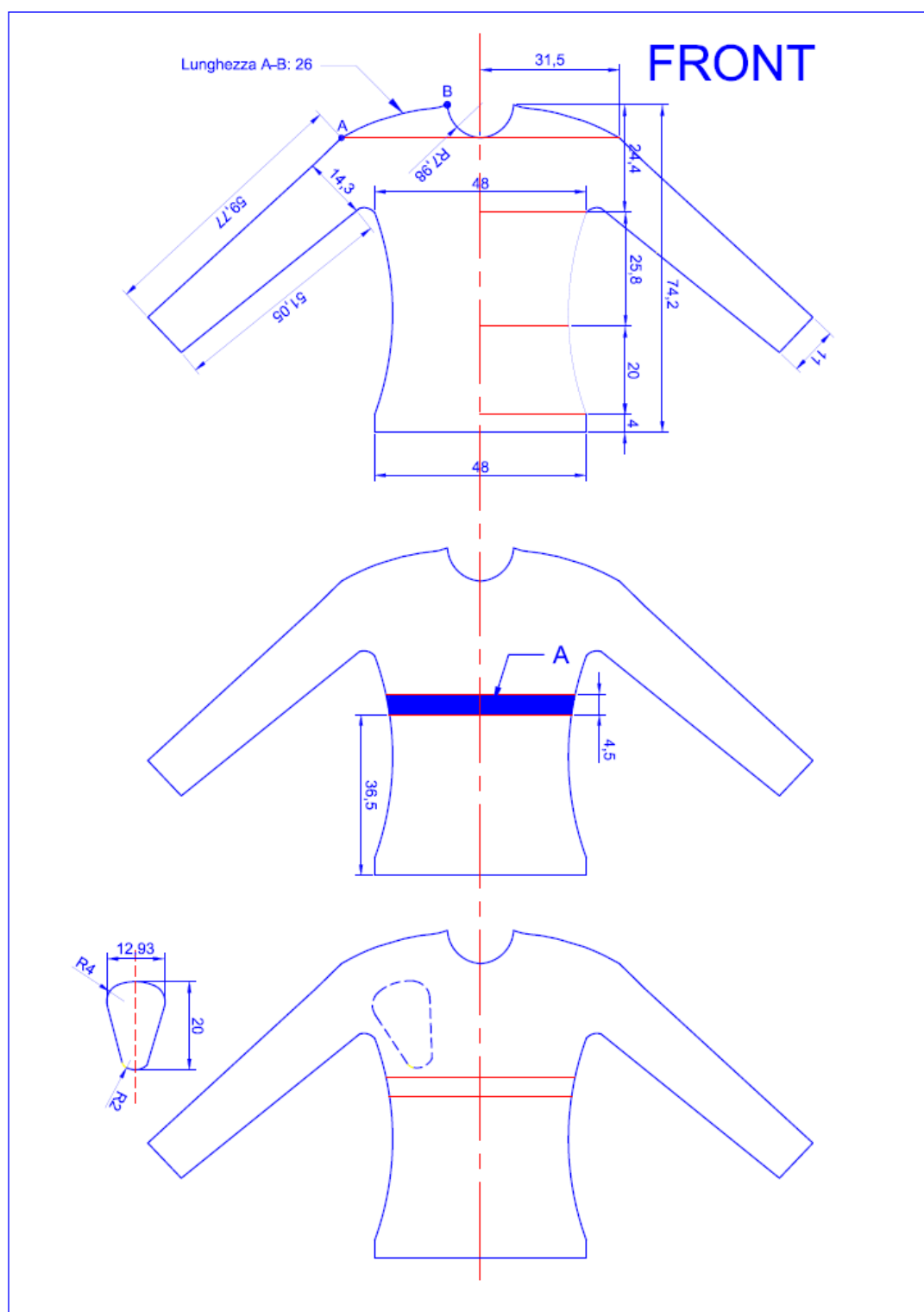


Fig.4.19 The second prototype front drawing (in cm)

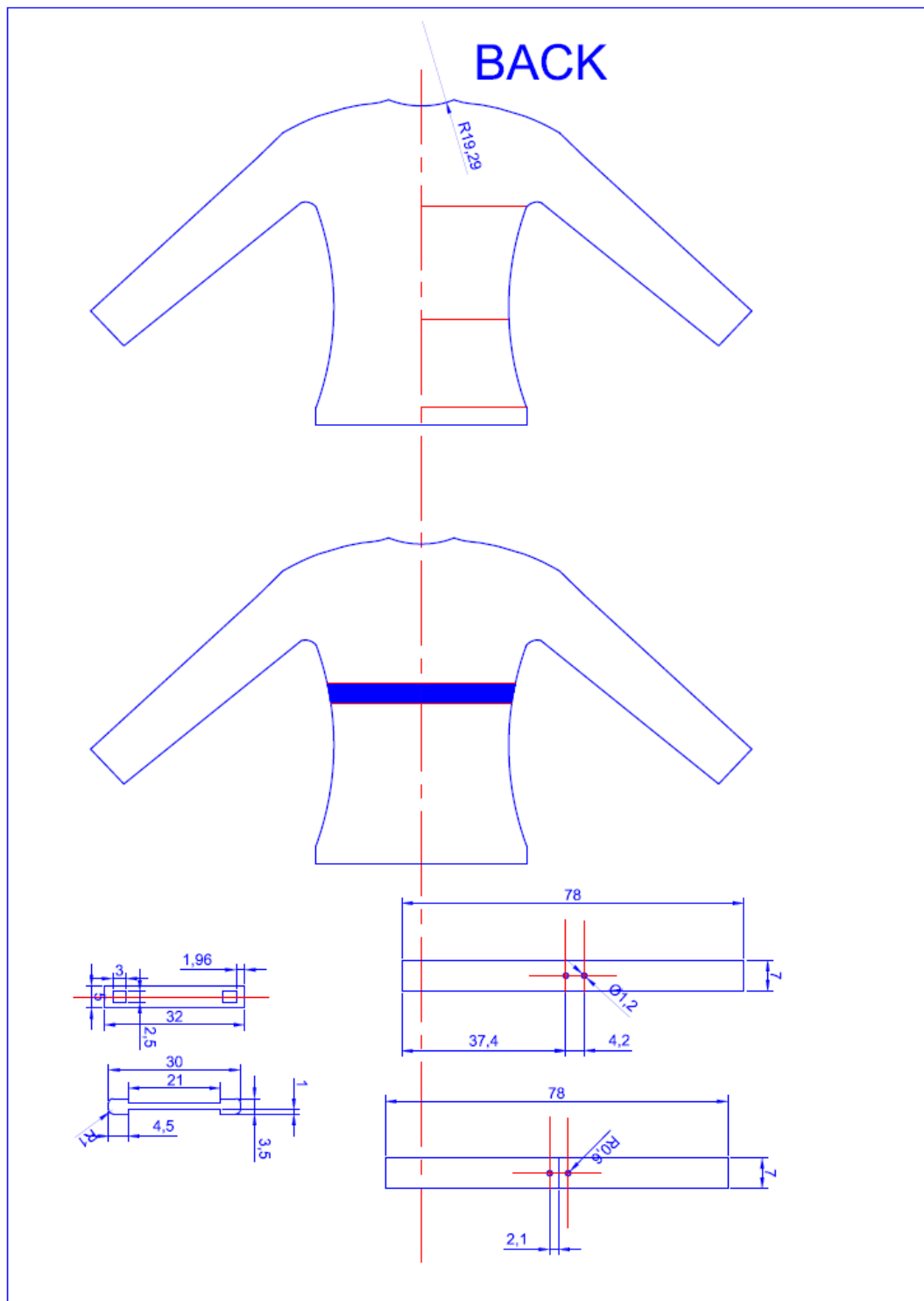


Fig.4.20 The second prototype back drawing (in cm)

The pattern on Fig.4.19 shows a hidden pocket inserted on right shoulder. This gives the possibility to transform the shirt by inserting a pad of D30 material (Fig. 4.21-4.22) for shock absorption and impact protection during activities like shooting.



Fig.4.21 The pad of D30 material to be inserted on the right shoulder



Fig.4.22 The second prototype with the pad

4.3.6 Testing

The testing phase consisted in evaluating the two prototypes starting with the biomechanical, ergonomical and physiological requirements of the end-user during different tasks.

We acquired the subject wearing the smart shirt with a real-time inertial motion tracking (Yost Labs 3-Space™ Sensor labs).

A Digital Human Modelling (DHM) of our soldier wearing the smart garment was created and used for the garment design and fit evaluation. Section 4.3.6.1 will describe a framework for design smart clothing in a DHM Belgium soldier avatar.

Section 4.3.6.2 we will show all the steps used into the garment co-design workflow for the design of our smart t-shirt for monitoring soldier's performance using DHM as data

representation of some human aspects. They can be inserted in a future simulations tool and facilitate prediction of usability, satisfaction, and performance.

4.3.6.1 Smart clothing into Digital Human Soldier

Digital Human Modeling (DHM) has mainly focused on kinematic and dynamic performances of humans in different applications. Nowadays the new availability of wearable technologies offers innovative possibilities to integrate other mechanical, environmental, and physiological parameters in an ecologic and non-intrusive approach. In fact, evaluating human performance and identifying critical factors is a challenge due to the high number of parameters of the problem and the multiple degrees of freedom. Stress, training, fatigue, load and environmental conditions have a great influence on human-product-task system performance. This is particularly true and critical in military applications.

If DHM offers the possibility to analyze and predict human posture, motion, and other functions in a high-fidelity, physics-based, three-dimensional, real-time environment, wearable devices allow for monitoring vital (heart rate, breathing rate, temperature) and emotional (HRV – Heart Rate Variability, EDA -ElectroDermal Activity) parameters, movements, and postures.

For this reason, they can be considered as a complementary analysis tool to DHM. The research presented in this chapter describes a framework for the design of smart clothing in a DHM Belgium Soldier avatar (Fig.4.23).

The innovative approach concerns a combination of a set of different digital technologies and applications to create a common co-design workflow for garment design.

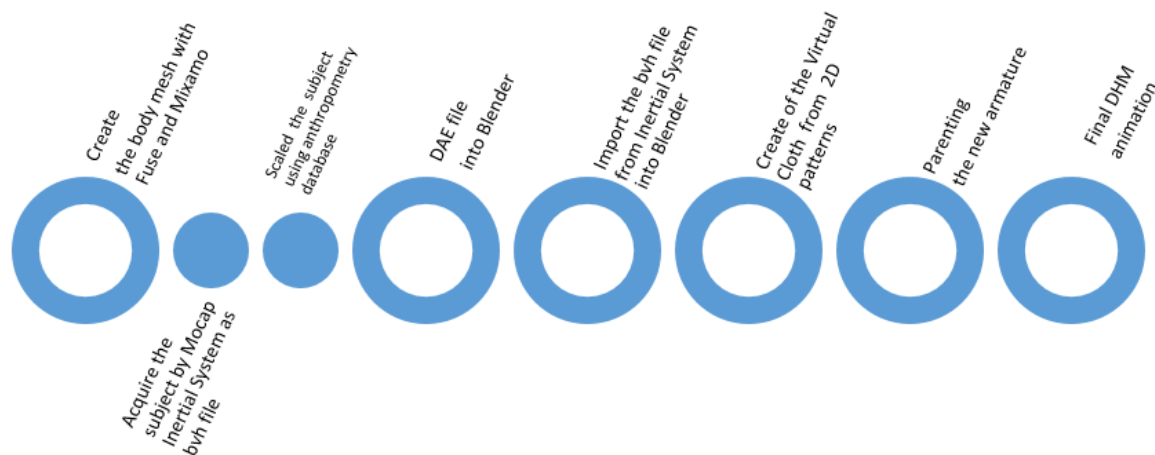


Fig.4.23 DHM workflow

The starting point of the virtual mannequin is the creation of the full humanoid mesh. The acquisition can be done through a body scanning system. In the market, it is possible to find low cost devices that can scan the body such as Microsoft Kinect [1] and or Artec [2].

In our case we did not acquire the body mesh, but we used Fuse [3] and Mixamo [4] to create the humanoid mesh. Starting from the Adobe Fuse CC (Beta) 3D modeling app, the

model was created using a library of high-quality 3D content consisting of faces, bodies, clothing, and textures. In Fuse CC it is possible to customize the color, texture, and shape of over 280 attributes, including hair, eyewear, and clothing fabric, to achieve the desired look. When you (Fig.4.24) change the size and proportion of the character's body, the clothing and other attributes adjust automatically (Fig.4.25).

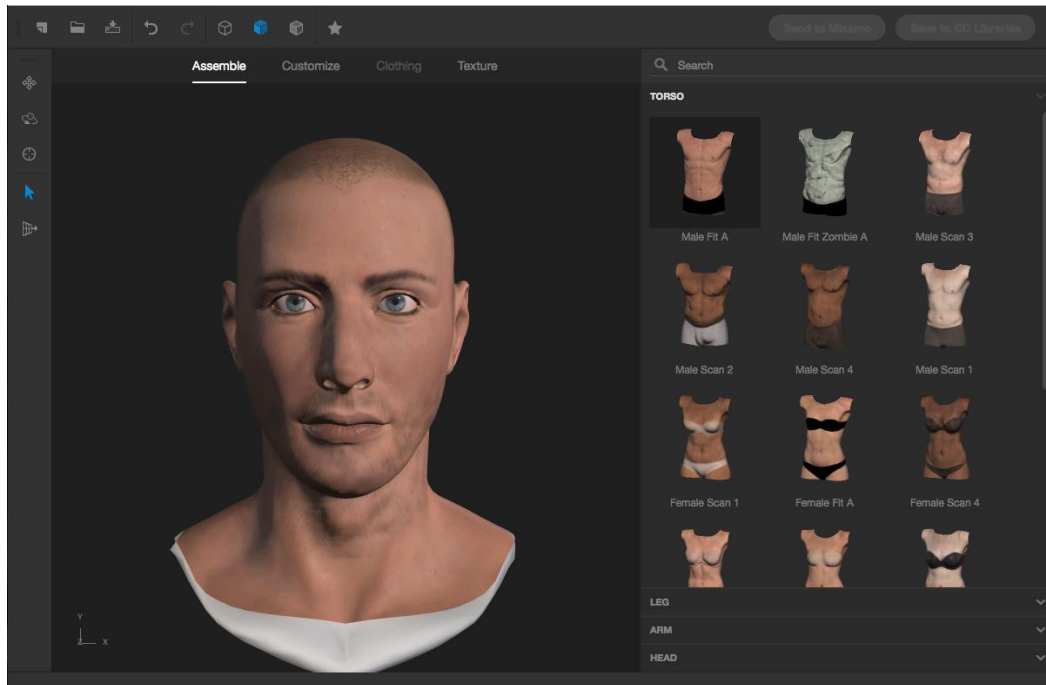


Fig.4.24 Assemble mode

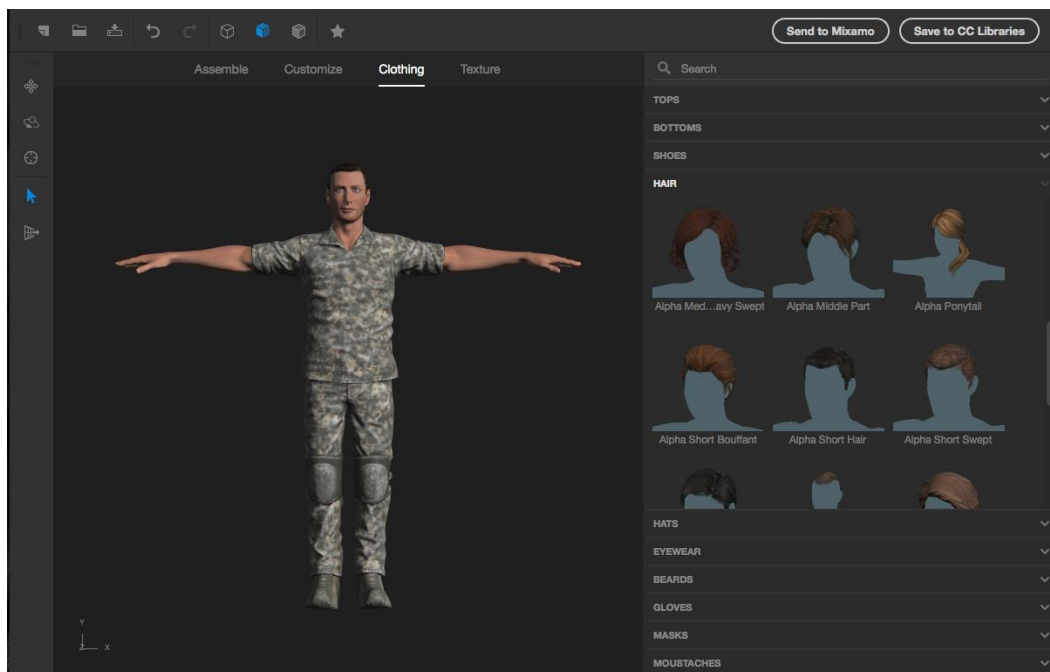


Fig.4.25 Clothing mode

The 3D characters were saved in a Creative Cloud Libraries (Fig.4.26) and then posed and animated with Photoshop CC and Mixamo's web-based animation service, and finally exported the animated model to a collada file (DAE format), Fig.4.27.

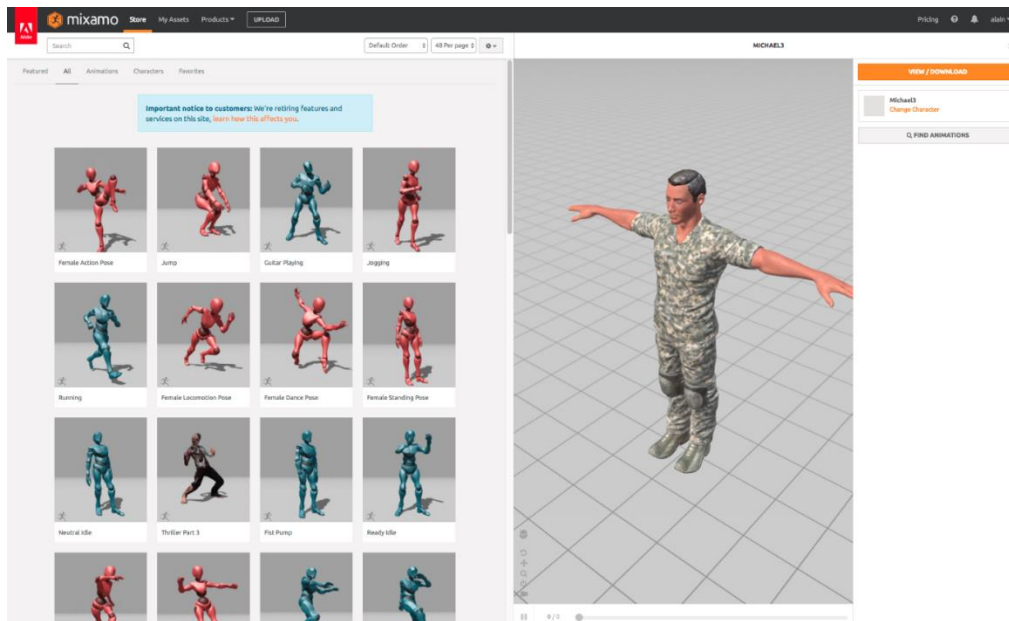


Fig.4.26 Creative Cloud Libraries

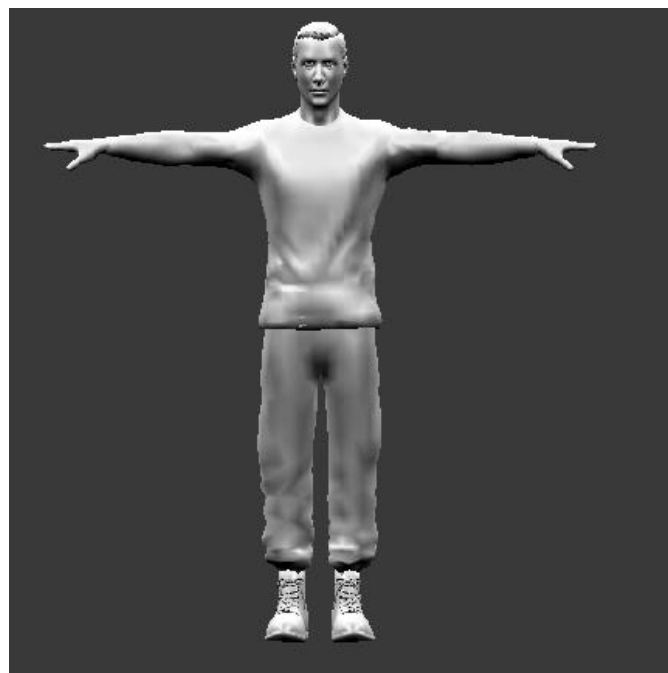


Fig.4.27 DHM collada file

Next, we acquired the subject wearing the smart shirt with a real-time inertial motion tracking system (Yost Labs 3-Space™ Sensor) [5] during a task (Fig.4.28).



Fig.4.28 The subject wearing the smart shirt and the inertial system

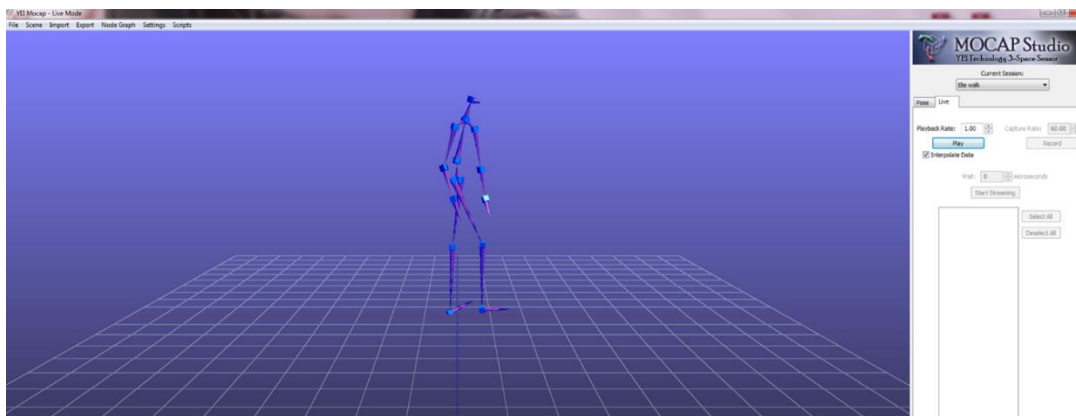


Fig.4.29 YEI Mocap Studio software data representation

For the next steps, Blender [6], an open source 3D modelling and animation application, was used for importing:

- 1) the DAE file
- 2) the armature from YEI Mocap Studio (Fig.4.29).

After importing the collada file (DAE format) in Blender, the successive step was the creation of the virtual clothes as a texture on the avatar. Focusing more on the upper body, the smart shirt was developed starting from the 2D patterns that were used to design the first prototype, (Fig.4.30). No animation was applied to the DHM (Fig.4.31). For the boots and the trousers, we used textures previously created in Photoshop. The same procedure was used for the second prototype (Fig.4.32).



Fig.4.30 The first prototype-front



Fig.4.31 The DHM with the first prototype



Fig.4.32 The DHM with the second prototype

Next, the armature (skeleton) acquired with a real-time inertial motion tracking system (Yost Labs 3-Space™ Sensor) was imported.

At that moment, we had two armatures:

- 1) the armature from Mixamo exported as collada file
- 2) the armature acquired with a real-time inertial motion tracking system.

The armature from Mixamo was eliminated (Fig.4.33) as originally part of the mesh.

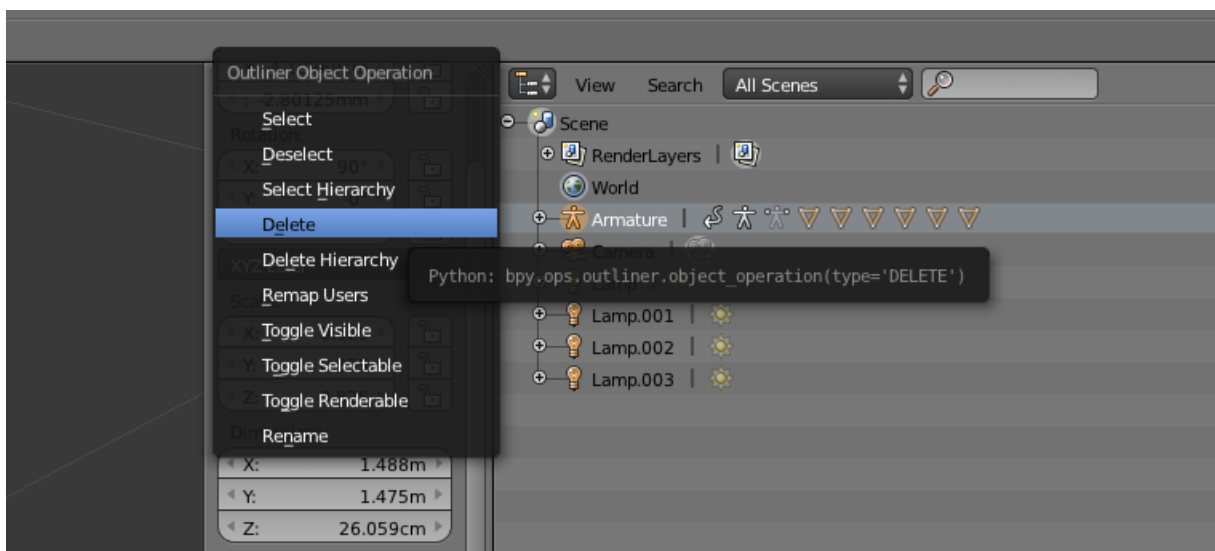


Fig.4.33 Armature elimination

The armature from the motion tracking system was aligned with the humanoid mesh, (Fig.4.34-4.35), the individual bones with the mesh were aligned, (Fig.4.36) and marked visible (Fig.4.37).

The following step was the automatic weights parenting calculating the influence of a bone on vertices based on the distance from those vertices to a bone ("bone heat" algorithm). This influence was assigned as weights in the vertex groups.

Weight painting mode was used to tweak what parts of the mesh were affected by each group, (RED=100% weighted, BLUE=0% weighted) (Fig.4.38) for the head and for the upper body (Fig.4.39-4.40).

A vertex may not only be a member of one or more vertex groups, but also may have a certain weight in each group. The weight symbolizes its influence on the result. The color visualizes the weight of each vertex of the currently active group. A vertex drawn in blue indicates either: a weight of zero, not in the active group, or not in any group at all.

We assigned the weight of each vertex by painting on the mesh with a certain color. Starting to paint on a mesh will automatically create a new vertex weight group (when no group existed or is active). If a vertex doesn't belong to the active group, it is automatically added even if you paint with a weight of "0".

The parenting was completed, the armature (skeleton) could move and the DHM was animated accordingly (Fig.4.41).



Fig.4.34 Armature from the motion tracking system half aligned with the mesh (front)



Fig.4.35 Armature from the motion tracking system aligned with the mesh (front and sagittal view)

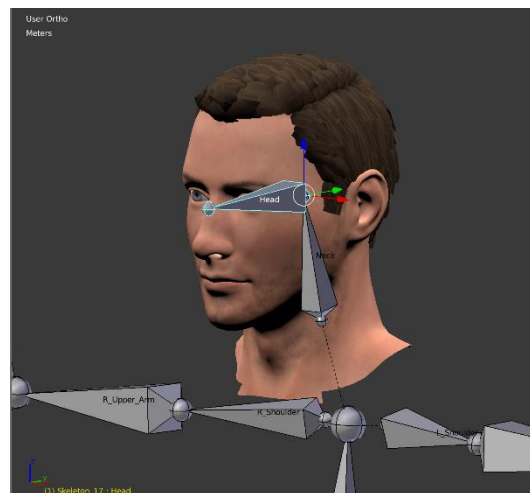


Fig.4.36 Individual bones aligned with the mesh

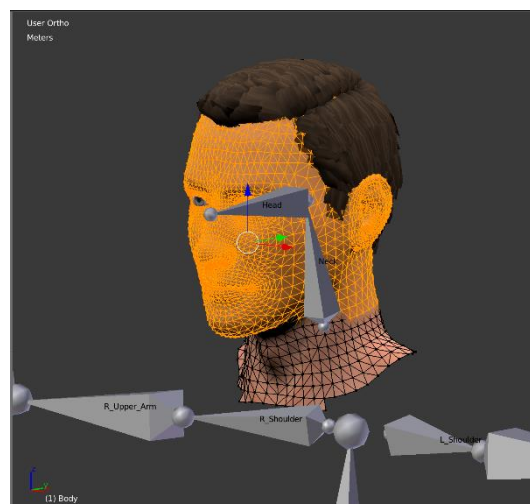


Fig.4.37 Head bones aligned with the mesh

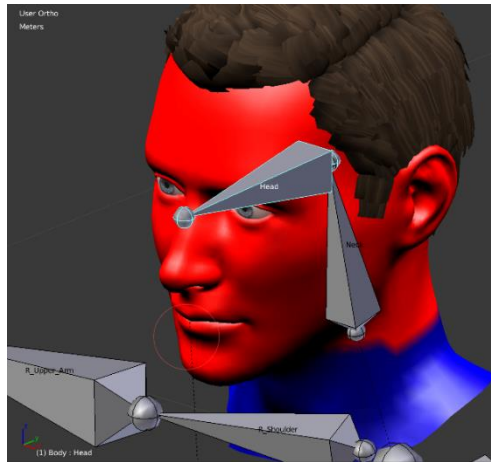


Fig.4.38 Weight painting (RED=100% weighted, BLUE=0% weighted)

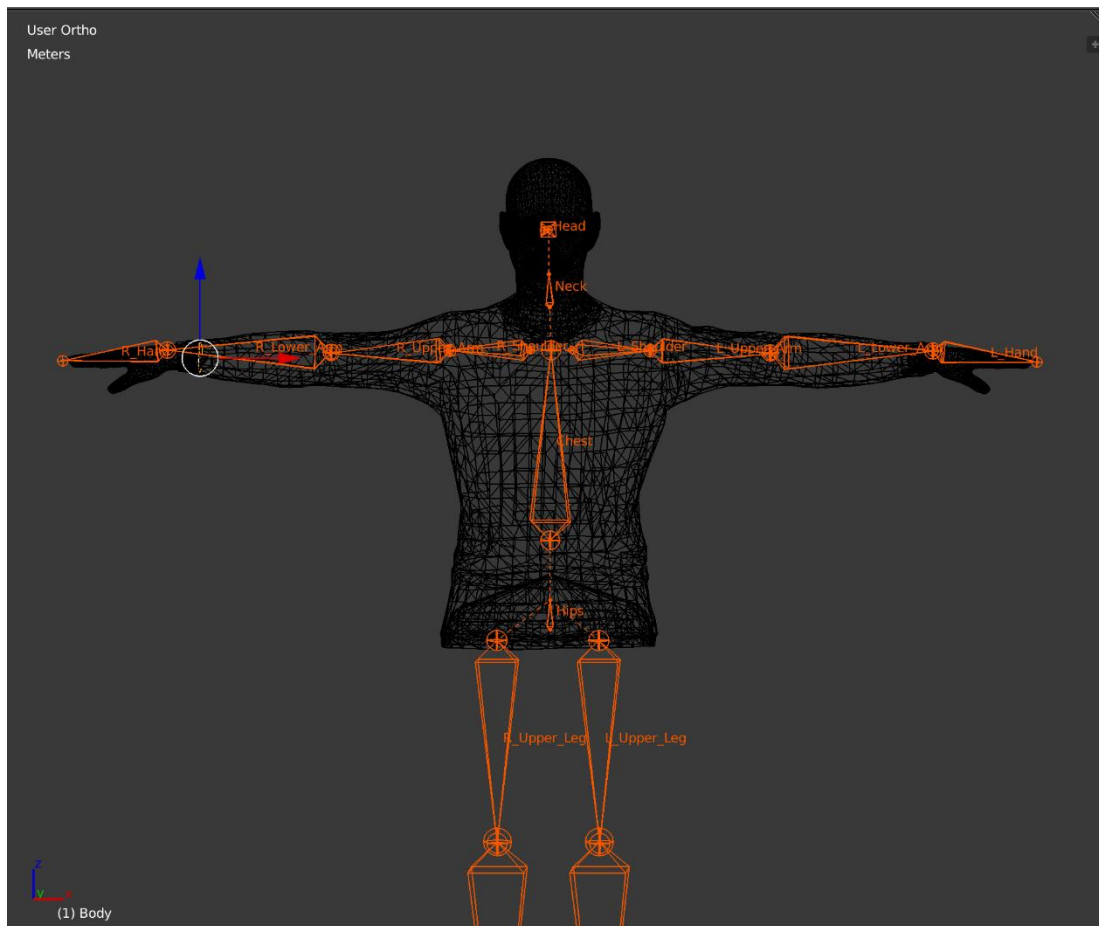


Fig.4.39 Upper body selection

Bibliography

[1] <https://developer.microsoft.com/it-it/windows/kinect>

[2] https://www.artec3d.com/3d-scanner/artec-eva?keyword=artec%20eva%20%2Bscanner&gclid=EAIaIQobChMIzKvn6bLg1QIViRobCh1pIA6QEAAAYASAAEgJo1PD_BwE

[3] <http://www.adobe.com/it/products/fuse.html>

[4] <https://www.mixamo.com/>

[5] <https://yostlabs.com/>

[6] <https://www.blender.org/>

4.3.6.2 Testing: ergonomical and biomechanical evaluation

The testing phase consisted in evaluating the two prototypes starting with the biomechanical, ergonomical and physiological requirements of the end-user during different tasks.

A Digital Human Modelling (DHM) of our soldier wearing the smart garment was created and used for the garment design and fit evaluation. Section 4.3.6.1 described a framework for the design of smart clothing in a DHM Belgium soldier avatar.

Two DHM were realized: the first one represents the soldier wearing the first prototype and the second one the soldier wearing the second prototype.

Next, every single 2D pattern was transformed with Photoshop (Adobe) in a texture able to create the smart t-shirt in Blender (see Fig. 4.42).



Fig.4.42 DHM (first prototype) and flattening of 3D patterns (front)

We repeated the same procedures for the second prototype (Fig.4.43).



Fig.4.43 DHM (second prototype) and flattening of 3D patterns (front)

Comfort includes the physiological and psychological aspects on the one hand, and the biomechanical and ergonomical aspects on the other hand.

More attention should be paid to understanding ergonomic issues, heat stress implications and the relationship between the task and the clothing. The degree of thermophysiological comfort is defined by the thermophysiological characteristics of the textile as well as a range of motion while performing a task. Starting from this assumption we evaluated the thermophysiological comfort of the two smart shirt prototypes using a thermal image from a FLIR camera, (FLIR, Wilsonville, OR, USA with an infrared resolution of 4,800 pixels, MSX resolution 320x240, thermal sensitivity below 0.15 °C, and accuracy of ± 2 °C) applied on the digital human model (DHM), (Fig.4.44-4.45).



Fig.4.44 Thermophysiological evaluation in DHM on the first prototype after 30 minutes of exposure



Fig.4.45 Thermophysiological evaluation in DHM on the second prototype after 30 minutes of exposure

Comparing the first prototype with the second we saw a strong difference in temperature between the first and the second prototype. The second prototype revealed to be more thermophysiologicaly comfortable than the first.

The second evaluation compares the two shirts in terms of limit of range of motion while we are performing a task like walking, running, jumping or climbing.

We start with the first prototype at the shooting range to verify a limit in flexion-extension during the aiming. Comfort questionnaires of ten volunteer subjects after the shooting give the same results revealing that the first t-shirt is uncomfortable on the armpit. This limits the range of motion on the shoulder during a simple gesture as a flex-extension.

The second t-shirt solved that limit due to the use of stretch fabric at the armpit. That feature allows us to extend the use of the smart t-shirt in sports where a high range of motion at the armpit is requested such as climbing, shooting, rowing, archery, basketball, volley-ball and especially military training (Fig. 4.46). A three-dimensional (3D) accelerometer on the trunk can quantify and evaluate the symmetry and the intensity of a motor task giving a complete evaluation of the performance (Fig. 4.47).

Iterative studies on the co-design workflow permitted us to define the final functional cloth that will be use for monitoring soldier's performance in terms of training, injuries, and psychological status monitoring. This technology can provide essential feedbacks enabling the development of strategies to increase resilience and prevent unacceptable impairment of performance.

The second prototype was finally tested in the water. Questionnaires for the subjects demonstrates that they preferred a shirt with a short sleeve or a vest to have freedom of movement and comfort in the water.

Starting from that, a third prototype was made and will be discussed in the next section 4.3.7.

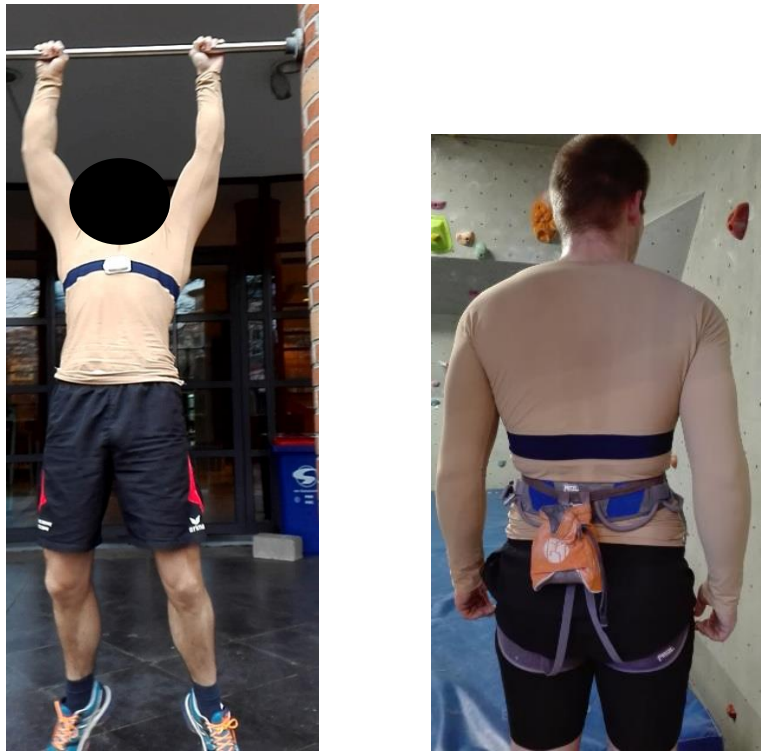


Fig.4.46 Use of the smart t-shirt during sport activity

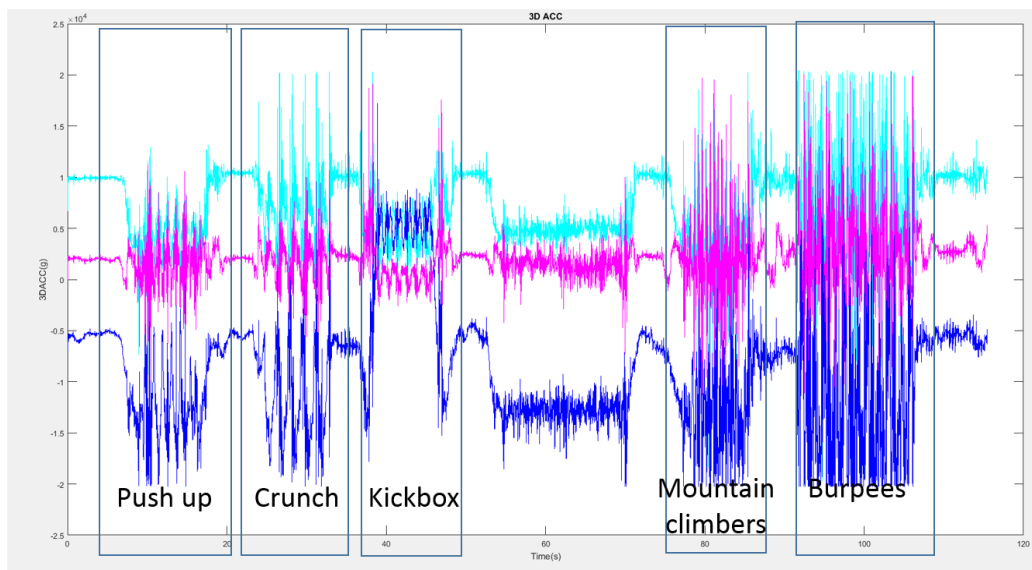


Fig.4.47 3D accelerations during sport training wearing the smart t-shirt

4.3.7 Third Prototype

The third draft involves another concept where three textiles compose the smart garment. The first one is represented by a red textile (72%Microfibre PA/28% EA(LYCRA®), 164g/m²), the second it is a red perforated textile on the back (72%Microfibre PA/28% EA(LYCRA®), 164g/m²) and the third one it is a belt red/green of bonded textile (72%Microfibre PA/28% EA(LYCRA®), 328g/m²) that contains the sensing technology.

This concept aims at reducing the number of patterns and consequently the number of joins of the fabrics permitting more comfort and flexibility. The third prototype was designed to be used in the water. The vest is a breathable fitting garment that gives freedom of movement (Fig.4.21-4.22-4.23-4.24).



Fig.4.48 The third prototype front



Fig.4.49 The third prototype back

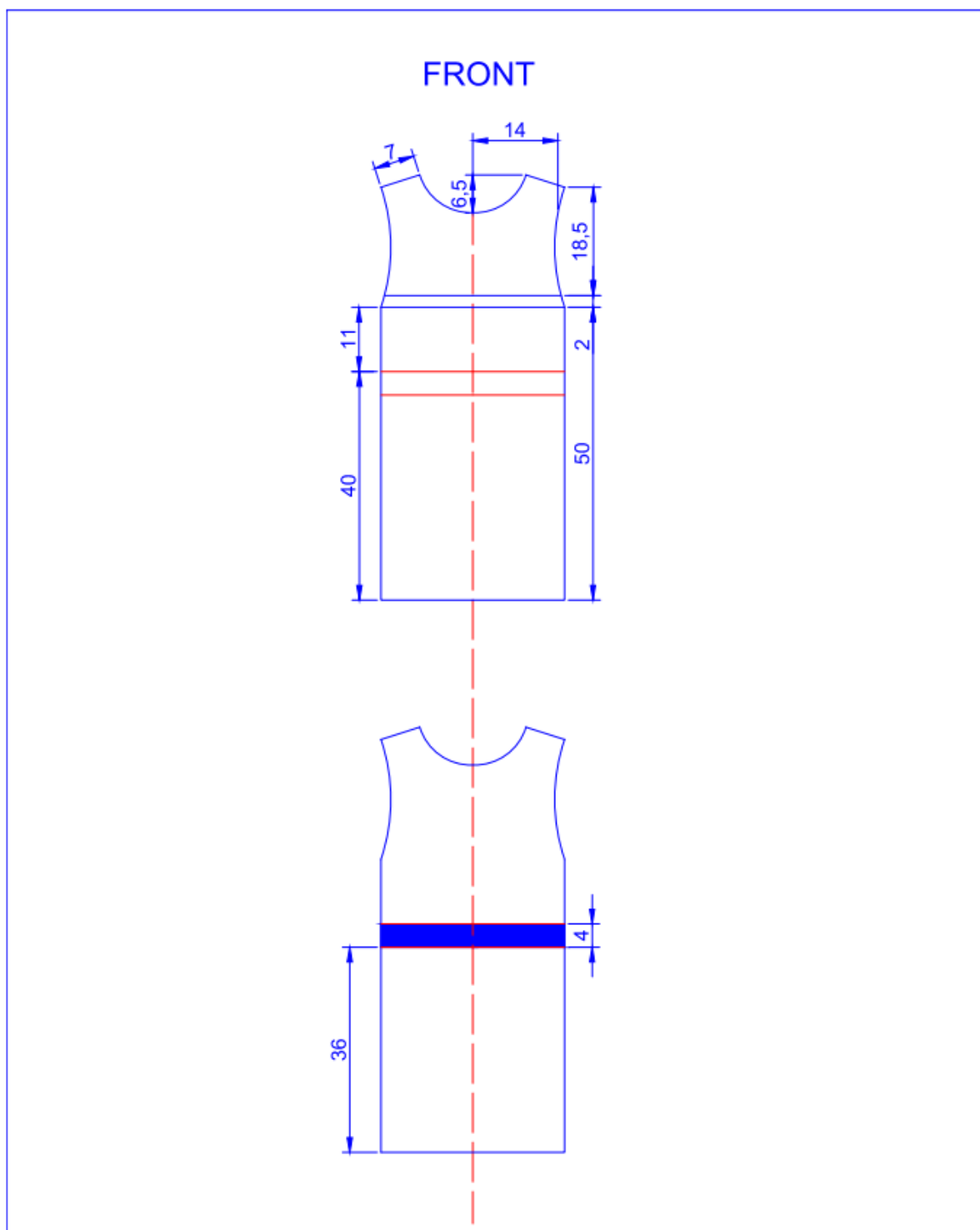


Fig.4.50 The third prototype front drawing (in cm)

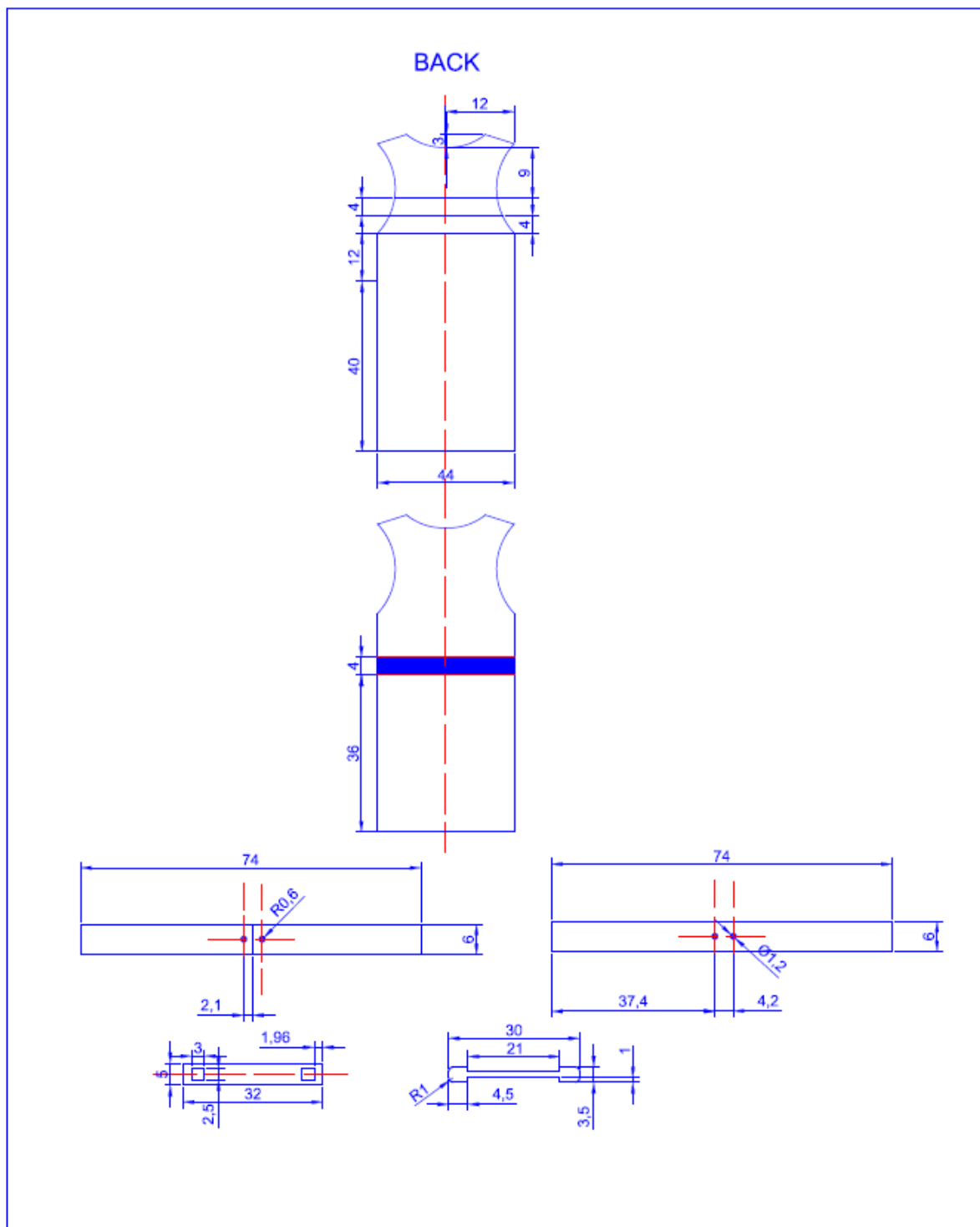


Fig.4.51 The third prototype back drawing (in cm)

4.4 Electronics package design

4.4.1 Introduction

The human body is not an ideal environment for electrical components. Design smart packaging requires to have a look at the entire human machine environment system. Dust, moisture, and water can damage the device. Design must address concerns regarding material interaction, reliability of the interface and impact on the entire human machine environment system. In this chapter the procedure that was applied for design the smart garment electronic waterproof package will be described (Fig.4.54).

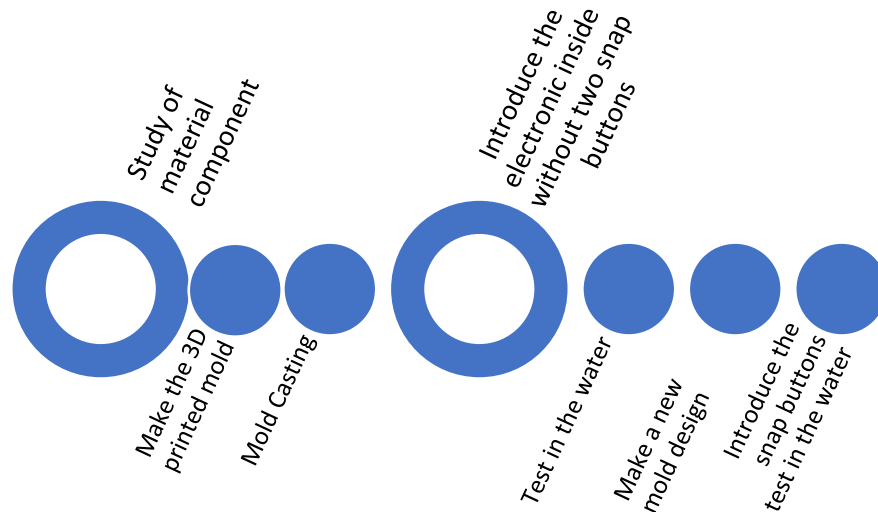


Fig.4.52 Smart garment co-design workflow

User engagement in the co-design process enabled the identification of user context and needs with the problematics of wearing the functional clothing and the wearable device hardware applied on it.

Starting from the available package, designed at POLIMI and manufactured with thermoformed material made of Teflon lacquered lira coupled to EPE 9003, the focus group started to test the available package with the smart shirt.

The results were that the soldiers were satisfied with the hardware technology (Fig.4.53), but they found anomalies in the external package design:

- The connection between the package and the smart shirt was not stable. This was revealed during activity like climbing or boxing.
- An example, during climbing a rope passed between the package and the t-shirt unplugging the package from the shirt.
- During boxing, the flexion of the shirt created noise with the package.
- During burpees exercise the package was not stable.
- The material is not water-resistant during outdoor activities. The color (white) of the package was not suitable for military activity. The package material got dirty easily and was not washable.
- The shape can be re-designed to be more ergonomical.

Focus group and briefing with experts in material science, design and electronics gave the opportunity to choose the material for the electronics package.

4.4.2 Design and material selection



Fig.4.53 The hardware

At the beginning three different materials were chosen: rubber, bi-component silicone and acrylonitrile butadiene styrene (ABS). The following parameters were evaluated: mechanical properties, the interaction between the material and the snap button, resistance against water ingress and the possible techniques for prototyping (Fig.4.54).



Fig.4.54 Materials interaction

The rubber was excluded because the low stiffness of the material didn't permit the snap button to be attached properly on a layer material. The component and the ABS were too rigid to be used for monitoring the chest movement. The ABS was not water resistant. For these reasons, all the materials were eliminated. It was decided to test a new material, highly viscous silicone which cures through polyaddition.

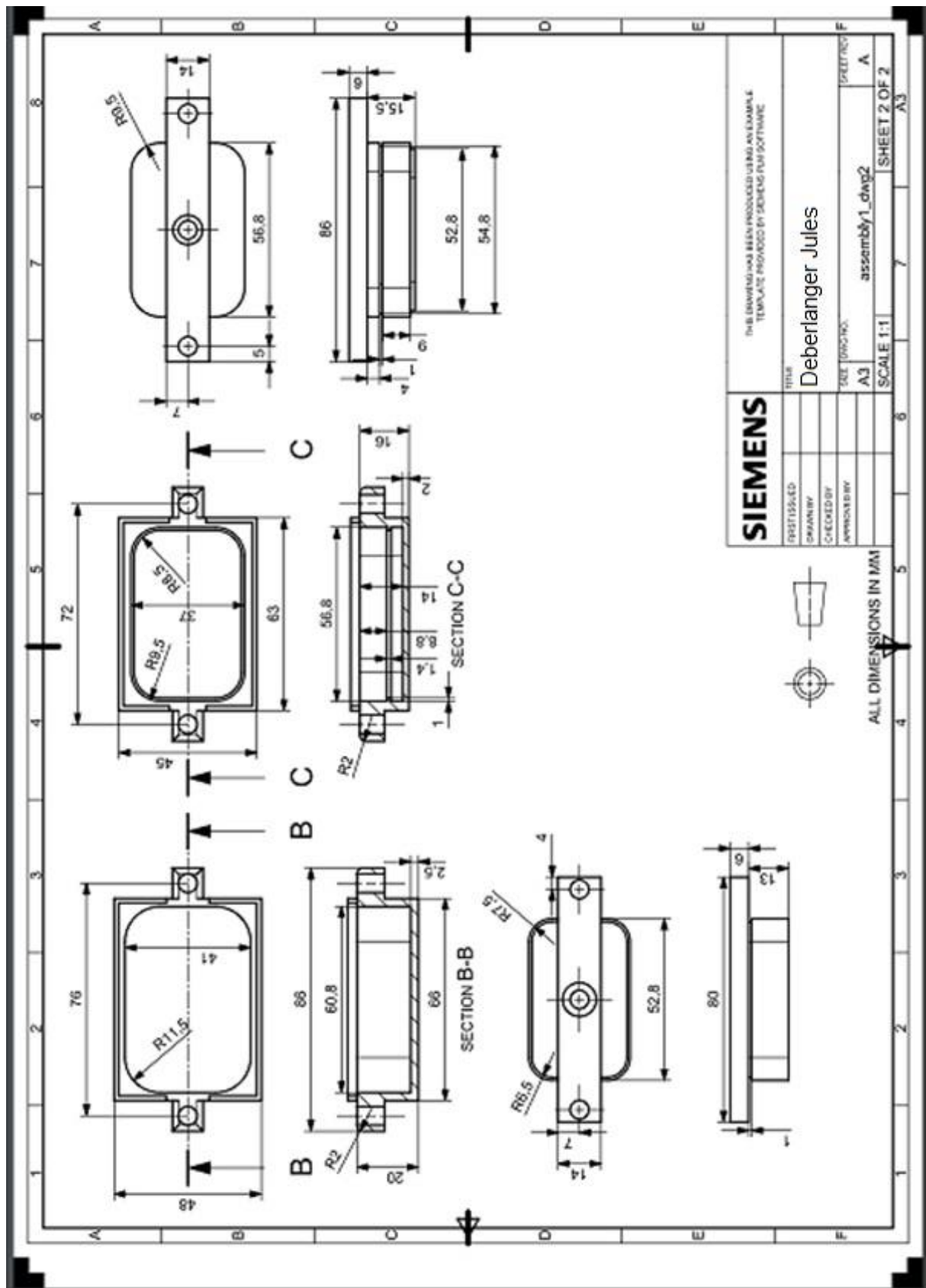


Fig.4.55 Technical drawing package

A 3D printed mold was designed to be fitted with electronics of the original package (Fig.4.55-4.56).



Fig.4.56 ABS mold

The silicon was poured through a syringe on the mold for the casting (Fig. 4.57).



Fig.4.57 Pouring mold method

The result was a silicon package of 26.67 g (Fig.4.58). To add stiffness to the package a rigid edge in ABS was made. Next step was the evaluation of the water ingress by inserting the package in a glass of the water (Fig.4.61).



Fig.4.58 Silicon package



Fig.4.59 Water ingress evaluation

The package was water-resistant for the limited column of the water in this glass. This gave the idea to test the Bluetooth communication through the water between the package and an external device such as a smartphone. In the first case a Samsung headset BTHM1000 was used to test the concept.

To prevent the water ingress and the destruction of the device, the headset was inserted in a plastic case (Fig. 4.60). The package was water resistant and the Bluetooth communication passed through the water (Figure 4.61).



Fig.4.60 Water ingress evaluation and BT communication

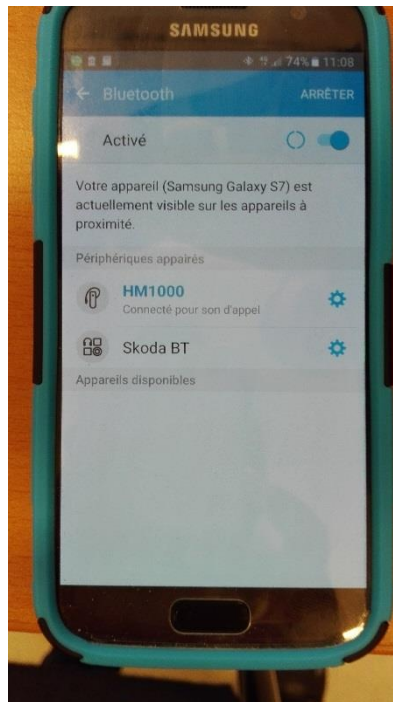


Fig.4.61 BT Communication

Successively, it was decided to test the BTcommunication in the water. It was sealed in a plastic bag and closed it into the package (Fig.4.62).



Fig.4.62 The hardware in to the package

To test it into deep water (70 cm), an experiment was designed where the package with the electronic inside was covered by silicon (Fig.4.63).



Fig.4.63 Pouring silicon to create an external mold

After the silicon dried, two holes were created and a cable of one meter was inserted to it as form a pendulum to simulate movements (Figure 4.64).

After switching on the device, the communication in real time between the package and the app was verified and recorded. As you can see in the figure 4.66 the 3D accelerations are represented in white, blue, and pink. The red is the ECG that in that case was not connected with the shirt.

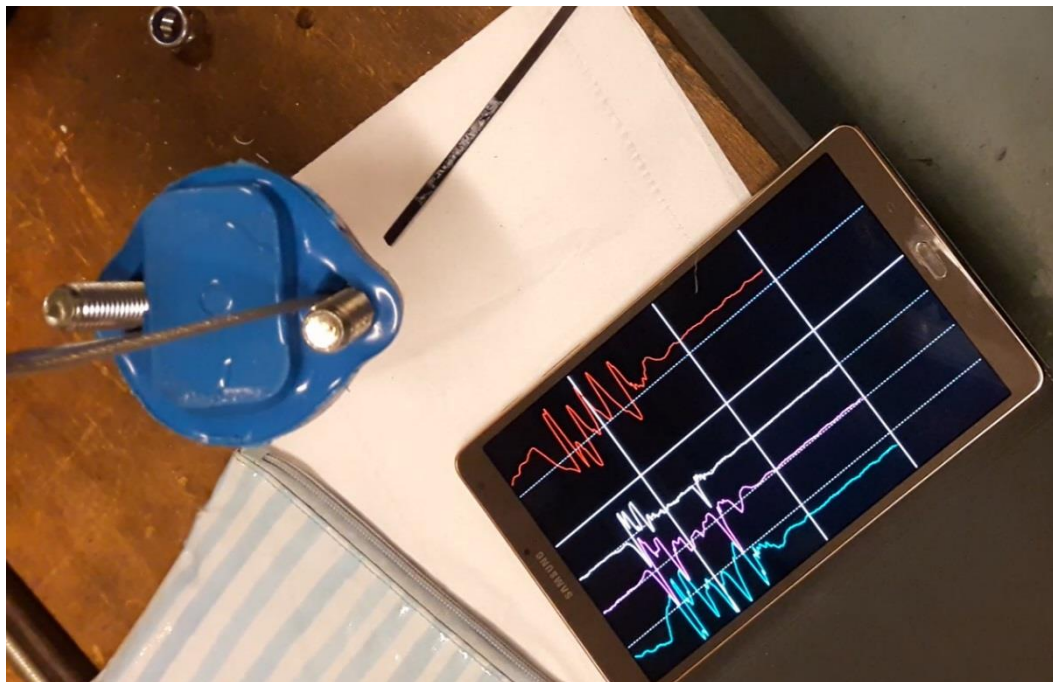


Fig.4.64 The BT Communication with an external APP

A graduated cylinder (70 cm) full of the water was used for the next experiment (Fig.4.65). The device was inserted in the water.

The Bluetooth communication between the device and the mobile app through the water was active (Fig. 4.66).



Fig.4.65 The experiment

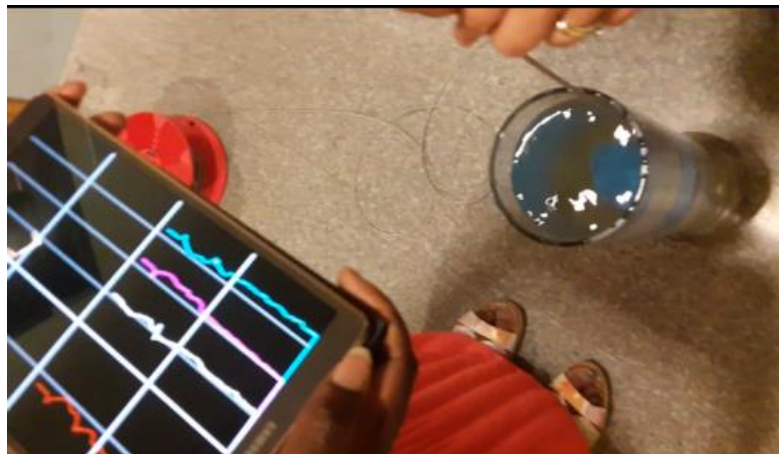


Fig.4.66 The Communication in the water

That revealed the capacity of the package to be water-resistant. The package was opened, and it was complete dry.

After having verified the weather tightness, the successive step was to re-design the mold studying two main things: the ergonomics of the chest (Fig.4.67) and the connection between the shirt and the package (Fig. 4.68).

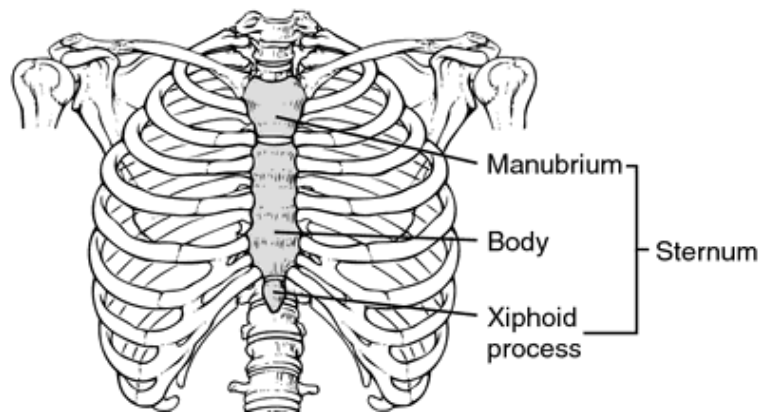


Fig.4.67 Thorax

A new mold was designed. Two different bi-component silicones were used for the experiment in the water: the first one opaque (blue) and the second transparent. The second demonstrates to be more intuitive due to the possibility to see the switch on the device.



Fig.4.68 The new package

4.4.3 Evaluation of the Bluetooth connection

Different experiments in the swimming pool, demonstrated the possibility to use the device for monitoring the subject into the water thanks to the possibility to store the data on a SD card or the possibility to transmit data in real time on an external device (tablet or smartphone) by Bluetooth for a short distance.

During these experiments the subject was immersed in the water and the real time connection stays for a short distance (< 100 mm) between the wearable device and the tablet held by a second subject outside the water.

The Bluetooth data transmission operating at the standard 2.4GHz had a hard time penetrating the water at long distance (> 100 mm).

To preserve the communication in real time, at longer distances, a repeater was ideated and attached to the back of the subject.

In fact, Bluetooth low energy is ideal for applications with low data rate and periodic intervals. Single mode Bluetooth at low energy devices are also smart devices optimized

for small battery-operated devices with low cost and power consumption as the BTM 182 used to the front [1]. Dual mode devices are known as Bluetooth smart ready devices. They include both Bluetooth low energy and classic Bluetooth. A typical example of dual mode are the smartphone or the Bluetooth serial port OBS421 connector [2].

You can use a connected low energy serial port service in smart clothing by using the dual mode Bluetooth serial port module OBS421.

The Bluetooth low energy BTM 182 communicates with the OBS421 which supports the same serial port Adapter AT Commands GATT (Generic Attribute Profile). GATT is used for service discovery as well as read/write values on a device. The basic operation of the Serial Port Adapter is to transmit application data between the serial port and a Bluetooth connection.

The GATT AT commands are enabled when the low energy is enabled. Indications for service changes might be received any time if the remote devices support the serial port device.

The Bluetooth Serial Port Adapter is a Bluetooth serial cable replacement module. The basic functionality is to transfer data between the serial port and a Bluetooth link. It is possible to configure a module to automatically setup a connection and/or accept an incoming connection. Configuration is done using AT commands.

The Serial Port Adapter can operate in three different modes; AT Mode, Data Mode and Extended Data Mode.

By default, the Serial Port Adapter will enter Data Mode and it must be configured to enter Extended Data Mode instead of Data Mode.

It enters AT mode by transmitting the escape sequence to the module. By default, the escape sequence is:

Silence 1 second

///

Silence 1 second

Please note that the /// must be sent within 200ms which means that it is difficult or impossible to enter the escape sequence manually using a terminal window.

Using the AT commands, it is also possible to configure the serial port adapter to work as a repeater (Fig. 4.69).

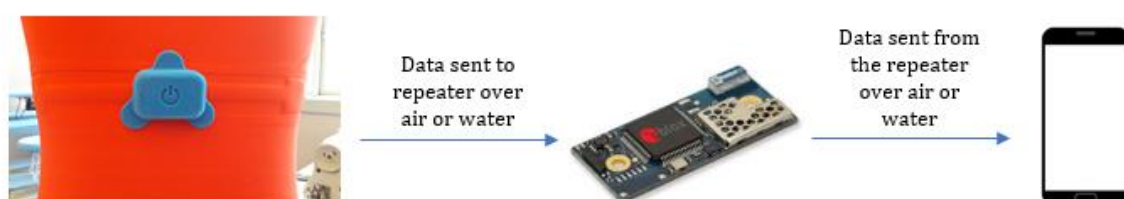


Fig.4.69 The communication in real time

The auto forward parameter enables the repeater functionality. Of course, this is only useful for the multipoint case since it requires at least two parallel Bluetooth connections. If enabled, data received from one Bluetooth channel is transmitted to all other Bluetooth channels. Data transmission over the serial port is disabled and it can only be used to enter the AT Mode and then execute AT commands.

To enable the repeater into the water, a second electronics waterproof package was realized with the same bi-component silicone and attached on the back of the subject. The repeater's package contains a small battery connected with a wireless circuit charging module. This gives the possibility to preserve the connection in real time through the water between the subject and the tablet.

4.4.4 Conclusion

This section presents the co-design workflow that was necessary in order to create a new electronics package design that can be used to monitor soldier's performance inside and outside the water.

Smart t-shirt monitoring capabilities can be extended from the lab to the field permitting a continuous monitoring of the wearer's performance. This is important in military field.

This study is a "work in progress". Further experiments on a wide population are required to validate the device.

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CHAPTER 5

New algorithms for monitoring performances

5.1 Assessment of Human Balance due to Recoil Destabilization using Smart Clothing (*)

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5.1.1 Introduction

This section presents a new assessment for human balance evaluation due to recoil destabilization based on trunk accelerometry measurements collected on the smart t-shirt and posturographical measurements by a force plate.

Recoil is the effect produced on humans by a shooting task provoking an external perturbation of the postural control system that can induce the resultant ground reaction forces (“center of pressure”) to exit from the base of support with the risk of falling.

Balance is a generic term describing the dynamics of body posture to prevent falling [1]. In upright quiet standing, humans are never in equilibrium, but they are stable. Their body returns to its mean position when it is pushed aside from the base of support [2]. The erect posture is regulated by control systems that organize the balance dynamically and depend on three actors: the sensory system, the central nervous system and the muscular and osteoarticular actuators.

The human body is mechanically unstable since its center of mass is located above its center of pressure on the ground. As soon as the resultant of the forces of gravity is no longer aligned with the resultant of the reaction forces on the ground, a torque is created which tends to accelerate the fall of the body.

The stabilization of this mechanically unstable body therefore requires a feedback control system whose inputs can detect any deviation from the “equilibrium position” to control the appropriate reactions to return to this “equilibrium” [3].

The output of a perturbation or input impulse is modulated by the state of excitation or attention of the individual [4,5].

The amount of attention is positively correlated with the regularity of the movement of the center of pressure (COP) [6] and during standing [7].

The postural stabilization is a synergy of different subcomponents [7-19]: sensory organization (visual, vestibular and proprioception), perception, motor coordination, biomechanics of the muscle-skeletal system and adaptation to the environment.

Shooting tasks require an alignment of the eyes (gaze effect) to the target while adopting a shooting posture that requires a lateral bend of the shooting hand trying to prevent the recoil destabilization by distributing the load forward during the aiming.

Normal balance requires control of both gravitational forces, to maintain posture, and acceleration forces to maintain equilibrium [20].

In quiet standing the multisegment chain that describes the biomechanics of the body can be simplified in a physiological condition, in a reverse pendulum simply hinged at the ankle with a single degree of freedom on the sagittal plane [1]. This model allows us to analyse the dynamics of balance taking into consideration two variables: the center of pressure (COP) and the center of mass (COM). The COM is the centre of the elements of mass that compose the body (body segments). Its position determines the lever of arm of the reaction force in comparison to the articulations and the sign of the corresponding moment of destabilization. The COP is the centre of pressures applied by every point of the surface of the foot in contact with the base of support. It deals with the point of application of the resultant of the strengths exchanged between foot and ground (strength of reaction to the ground). The position determines the arm of lever of the external strength of reaction (F) in comparison to the articulations and the sign of the correspondent reactive moment.

The COM influences the real movements of the body segments while COP, reflects the action of the muscular active strengths. The COP is the key in the analysis of the postural control.

The postural control system also employs open-loop control schemes and strategies [21], the output of which may take the form of descending commands to different postural muscles.

A right-handed rifle shooter must have enough extensibility of the hip flexors, the left iliotibial band, right high adductors, spinal musculature, and wrist flexibility to assume a stable position requiring a little amount of muscular activation [22]. Maintaining of upright posture during a perturbation, like recoil, depends on a synergy of several muscle contractions to maintain the center of mass inside the base of support [23].

In particular, at the moment of aiming the load is transferred on the right hip and it is supported by the upper body. Each knee and ankle transfer the occurred load to the hip [24]. Also, balance training can influence shooter's performance.

Braune et al. [25] were the first who evaluated the position of the center of gravity on human balance and in shooting.

Elite shooters have higher stability than untrained control subjects [26] and non-elite shooters [27-28]. Shooters can improve their stability in the last few seconds preceding the shot [28-29].

Experimental data proved that shooters adopt a mechanically unstable posture as consequence of the interactions among body segments [30].

Higher balance of an athlete is obtained by training [31-34] and also by paying attention to proprioceptive and visual cues [35].

Performers focusing on their body movements, or on an action that occurs in close proximity of the body, maintain a more stable posture than performers focusing on a more distant effect [36].

Motor training can improve performances requiring a cognitive reorganization of motor cortex [37].

The central nervous system is perfectly capable of predicting the trajectory of a movement that it controls and sees over a few tens of milliseconds. Recoil destabilization affects soldier performance. Motor learning plays an important role and therefore training, and experience can influence the soldier's performance significantly [38-39].

Mononen et al. [40] found that postural balance is related to shooting accuracy both directly and indirectly by shooting through rifle stability.

Skilled shooters employed a smoother and more efficient rifle movement while aiming than less-skilled shooters [41].

The shooter organizes to predict the moment of the shot by observing the vertical movements of the line of sight, predicting the trajectory of this unique movement, since the body is practically immobile in this plane [42].

The possibility of simultaneously following during firing, the shooter's center of gravity oscillation and the line of sight, explains this inability. This shows the independence between the weapon and body movements.

But when the movement of the weapon is not correlated with the movement of the body, then he needs to predict two different trajectories, which he monitors by two distinct mechanisms: one visual and conscious (the movements of the weapon), the other blind and unconscious (the fore-and-aft movements of his body) [43].

The movement required to pull the trigger is independent of body sway but can cause the movement of the weapon, influencing the performances [44].

Posturography (stabilometry) [45] is the science that studies the mechanism in postural control alteration due to a perturbation to obtain balance and stability.

Force plate and pressure plate are the common instruments for measuring postural sway in clinical setting.

Researchers already used force plates to evaluate postural stability in shooting measuring displacements of the COP [46-49].

Body-worn accelerometers have been proposed as a portable alternative and inexpensive wearable health systems (WHS) for sway measurements [50-54] but not yet for recoil destabilization analysis.

Moreover, the evolution of "the wearable era" brings the introduction of "intelligent textile" where the technology is embedded in the cloths in a non-intrusive and ecological approach [55-56]. The estimation of human trunk movement using smart clothing is already done [57-58].

5.1.2 Material and Methods

5.1.2.1 Subjects and Protocol

Four volunteer soldiers at Belgian Royal Military Academy participated in the research study aged between (21-30). The characteristics of the individuals who participated in the study are described in Table 5.1.

Tab.5.1 Main anthropometric properties of the individual that participated in the study

	Height (cm)	Body mass (kg)	Shoe size	BMI(kg/m²)
1	182	89,5	44	27,03
2	180	78,0	45	24,07
3	178	70,0	43	22,15
4	197	95,0	45	24,48

Subjects were asked to perform four trials of one single shot pointing at the target at 7 m distance, standing in a shooting position on a pressure plate, wearing the smart t-shirt. At the beginning of the session, each volunteer was asked to wear and test the smart t-shirt standing on a force plate in aiming position. A high-speed camera was also placed perpendicular to the sagittal plane of the shooter (Fig.5.1).



Fig. 5.1 Set-up illustrating the alignment of measured axis

5.1.2.2 Instruments

Shooting balance was measured with a one-meter footscan system (RSscan, Belgium) pressure plate with 8192 active sensors at 100 Hz.

The plate was triggered automatically by foot contact. Data export in Excel of the center of pressure (COP) was obtained by the footscan balance software.

Trunk accelerometry was collected by a 3D chest-worn accelerometer (MMA7361L, Freescale) of the smart t-shirt [59]. Data can be stored in the garment and can be connected by Bluetooth with an app for real time acquisition.

5.1.2.3 Data analysis

Two custom MATLAB (MathWorks, Natick, MA) scripts were built to acquire, store and analyze different components of posturographical data by the pressure plate and the 3D trunk accelerations.

A first program was used to calculate the posturographical data of the moment of the shot collected by the COP measurements of the force plate and exported as excel file.

Manually, we were able to extrapolate the COP data at the moment of the shot (Fig.5.2).

According to Schubert et al. [46], we calculated time domain posturographical data starting from 1-dimensional COP anterior-posterior (COPap.) and COP medio-lateral (COPml.) as can be seen in the table 5.2.

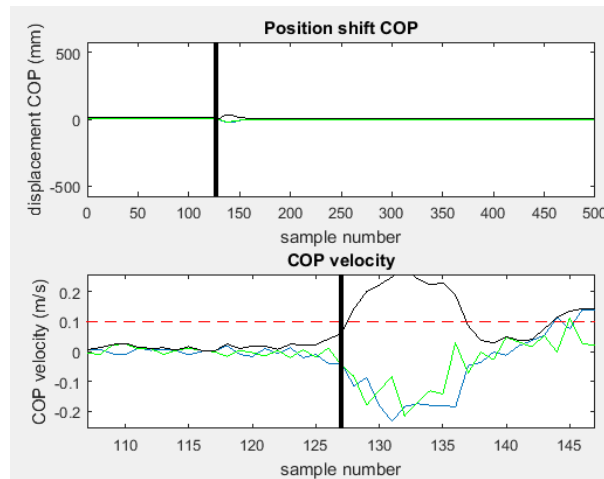


Fig.5.2 Shot event extrapolation by the force plate in Matlab

Measures	Description	Matlab Script Formula
COP distance	Mean distance from the center COP(mm)	$\text{mean}(\sqrt{\text{COPap.}^2 + \text{COPml.}^2});$
COP length	Total length of COP trajectory(mm)	$\text{sum}(\sqrt{\text{diff}(\text{COPap.})^2 + \text{diff}(\text{COPml.})^2});$
RMSap. and RMSml.	Root mean square of COP time series(mm)	$\sqrt{\text{sum}(\text{COPap.}^2)/\text{length}(\text{COPap.})};$ $\sqrt{\text{sum}(\text{COPml.}^2)/\text{length}(\text{COPml.})};$
Rangeap and Rangeml	Range COP(mm)	$\text{range}(\text{COPap.}); \text{range}(\text{COPml.});$

Tab.5.2 Posturographical parameters calculated from the force plate (all data in mm)

From the COPap. and COPml. we are also able to calculate the statokinesiogram (Fig.5.3) and the stabilogram for each shot.

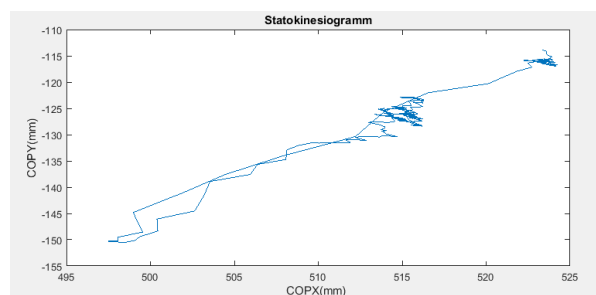


Fig.5.3 Sway path (statokinesiogram) at the shot event

A second Matlab program was written in order to detect the peak corresponding to the shot by the trunk accelerometric data (Fig.5.4).

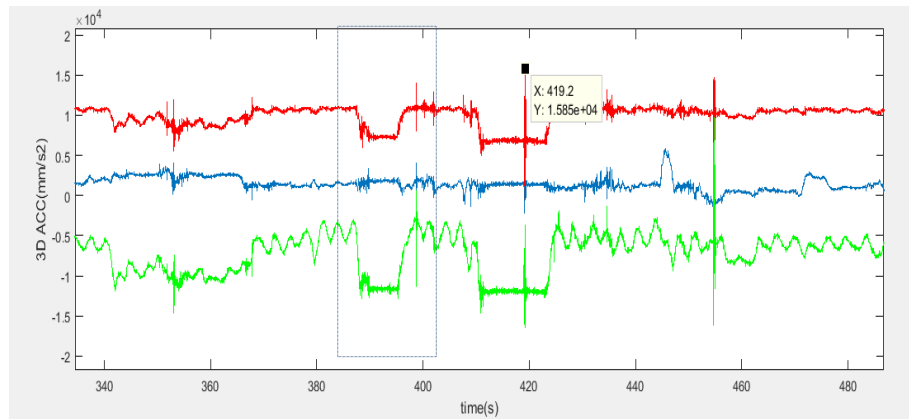


Fig. 5.4 Shot event solution based on 3D accelerometric data

The shot is fired at 419,2 sec. Starting from the peak of the shot calculating 3DACC(x,y,z) before and after the peak of a total half second as is marked in figure 5.4.

The 3DACC(x,y) components at the shot were computed for calculating the time domain measure of the trunk posturographical data [46] as described in Table 5.3.

Measures	Description	Matlab Script Formula
COP distance	Mean distance from the centerCOP(ACC)	<code>mean(sqrt(COPap.^2+COPml.^2));</code>
COP length	Total length of COP(ACC) trajectory(mm)	<code>sum(sqrt(diff(COPap).^2 + diff(COPml).^2));</code>
RMSap.; RMSml.	Root mean square of COP(ACC) time series(mm)	<code>sqrt(sum(COPap.^2)/length(COPap));</code> <code>sqrt(sum(COPml.^2)/length(COPml));</code>
Rangeap.; Rangeml	Range COP(ACC)	<code>range(COPap); range(COPml);</code>

Tab.5.3 Posturographical parameters calculated from the body-worn accelerometer (all data in mm/s²) and the Matlab related script formula.

Sway path (statokinesiogram) by trunk ACC in the moment of the shot are shown in Fig 5.5.

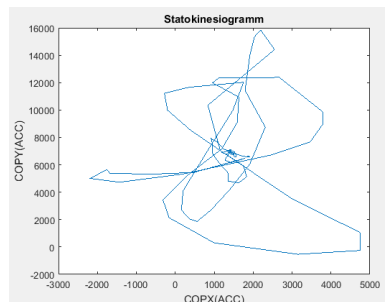


Fig. 5.5 Sway path (statokinesiogram) by trunk 3DACC(x,y) at the shot event

Mean ACC-based measures of sway were compared with the mean posturographical measures obtained by the pressure plate through linear regression using COP distance, COP length, RMSap-RMSml, Rangeap-Rangeml values calculated with both devices for the 16 shots. All statistical analyses were conducted using Minitab statistical software and are described in Table 5.4. Correlation between COP and ACC measures are also reported.

Trajectory Measures	Mean-COP(mm)	Mean-ACC(mm/s²)	r	p-values
DIST	12.55	8853.41	0.109	0.689
RMSap.	13.15	107.42	0.466	0.069
RMSml.	13.41	276.92	0.568	0.022
Rangeap.	52.93	12066	0.198	0.463
Rangeml.	41.72	12036.19	0.076	0.781
Sway path	310.13	89481.43	0.108	0.691

Tab.5.4 Correlation of COP and ACC-based measures

Mean RMSap (ACC) and Mean RMSml (ACC) were found to be significantly associated with the Mean RMSap. and Mean RMSml. predicted by the force plate. Anthropometrical data (height, body mass and shoe size) were also correlated ($p < 0.05$) with the Mean RMSml as are described in table 5.5.

Mean	Body mass(kg)	Height(mm)	Shoe size	BMI(kg/m²)
RMSap.	-0.752	-0.686	-0.661	-0.451
(ACC)[mm /s ²]	0.001	0.003	0.005	0.079
Sway path[mm]	-0.794	-0.770	-0.732	-0.620
	0.001	0.001	0.001	0.010

Tab.5.5Correlation of ACC-based measures RMSap and mean anthropometrical measures

5.1.3 Discussion

The chest worn accelerometer on the smart cloth reveals a good capacity to discriminate posturographical accelerometer based measures.

The correlation between the two devices was significant considering the RMS measure in the anterior-posterior and in the medio-lateral direction (Table 5.4).

A higher value was found in RMSml due to the fact that at the moment of the shot the subject ('right handed') transfers the load to the right hip (hip strategy) and is supported by the upper body. Question arises if also anthropometrical variables at the shot moment can influence the RMSap. (ACC).

High negative correlation with ($p < 0.05$) was found between RMSap. and height, shoe size and body weight respectively (Table 5.5).

During the shot the body mass index of the subject was an important factor for recoil impact force attenuation expressed by a correlation of $r = -0.620$ with ($p < 0.01$).

As while, if the body is represented by an inverted pendulum height and the shoe size (base of support) have a negative correlation with RMSap. (ACC). The sway path is related

to ankle strategy that is affected by body mass, height and ankle stiffness with high correlation as demonstrated in Table 5.45.

5.1.4 Conclusion

The use of smart clothing based on a chest worn accelerometer showed a good capacity to discriminate posturographical measurements for human recoil balance destabilization compared with the force plate.

Smart clothing reveals to be a non-intrusive garment for the study of recoil destabilization that can be adopted in different environment in an ecological approach. The added value is also the capacity to add a physiological evaluation of heart rate variability by the two electrocardiographical (ECG) textrodes embedded into the cloths.

Future work will address the evaluation of heart rate variability measures with the same protocol to have a more complete assessment for monitoring recoil destabilization.

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5.2 Heart Rate Variability in soldier's performances (*)

(*) Scataglini S., Truyen E., Perego P., Gallant J., Van Tiggelen D., Andreoni G.
"Smart clothing for heart rate variability measures in military", HBIM Journal July 2017.

5.2.1 Introduction

Intensive military training, missions and fatigue can create Post Traumatic Stress Disorders (PTSD) and Physical Exhaustion (FPE) affecting soldier's performances. Heart rate variability (HRV) is a physiological measurement of the autonomic activity of the heart. The autonomic nervous system actively compensates for injury or fatigue by modulating the balance between parasympathetic and sympathetic cardiovascular control mechanisms. Heart rate variability (HRV) is the physiological phenomenon of variation in the time interval between heartbeats. It is measured by the variation of the beat-to-beat interval.

Methods to detect beats include: electrocardiographical (ECG), blood pressure, ballistocardiograms [1-2] and the pulse signal derived from a photoplethysmograph (PPG).

Other terms include "cycle length variability", where R represents the peak of the QRS complex of the ECG wave. RR represents the interval between successive R. Sometimes the term RR is replaced by NN meaning that the beats are normal.

To detect changes over a period of hours requires a large volume of data to be collected and analysed. Holter devices can record the ECG in subjects from 24 hours to weeks. Smart clothing revealed to be a good alternative for physiological monitoring [5].

The smart cloth for monitoring soldier's physiological status is based on a wearable textile electrode ("textrode") technology for ECG measurements.

Heart rate variability measurements in time and in frequency domain were extrapolated through a MATLAB algorithm that works offline on time intervals between successive heartbeats from ECG recordings collected by the two textrodes embedded in the cloth. The innovative marks of the study stem not only from the ability to optimize the evaluation in terms of human resources and the non-invasive way for humans but also from the possibility to implement a new tool for the evaluation of soldier's physiological status.

5.2.2 Heart Rate Variability analysis methodology

Two textrodes made by conductive material were embedded into the clothes enabling transthoracic electrical bioimpedance measurements. Two snap buttons were used to provide the connection between the shirt and the hardware unit (Fig.5.6).

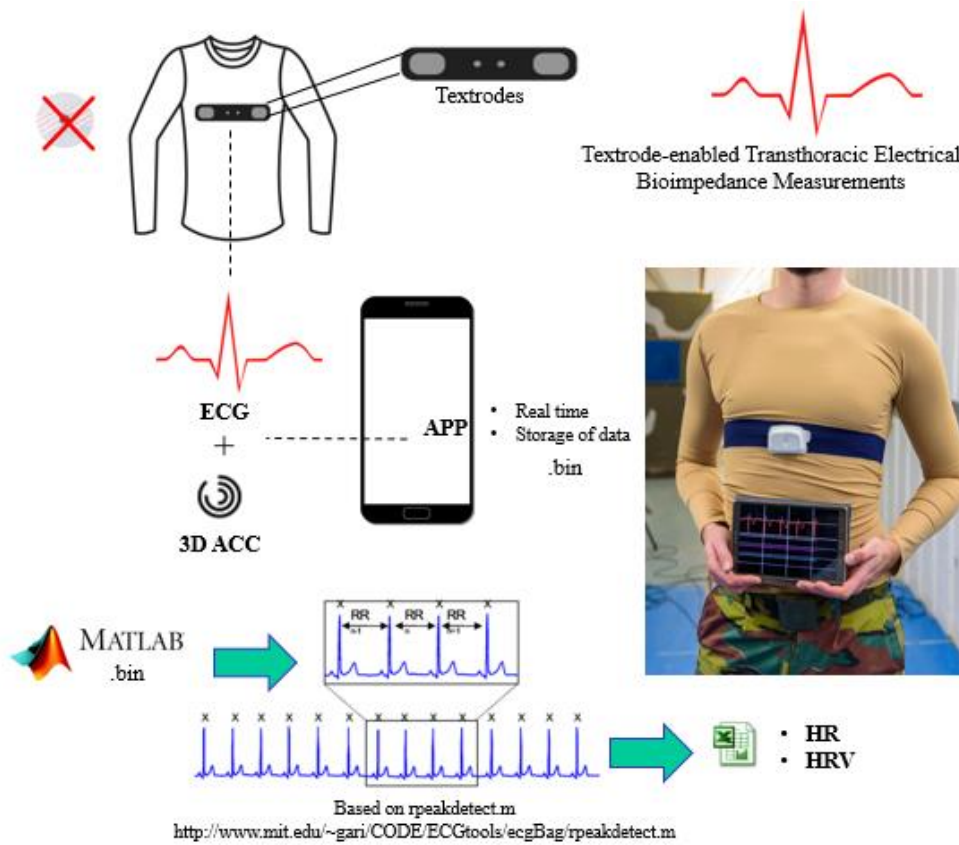


Fig.5.6 The smart shirt system

A MATLAB function `rpeakdetect.m` [6] written by G. Clifford (gari@ieee.org) and made available under the GNU public license was used to extract the heart rate (HR). This function used a batch QRS detector based on the one proposed by Pan et al. [7]. This solution allowed to detect the QRS complex and to identify the R-peak occurrence. HRV can be assessed with various analytical approaches, although the most common are the time domain and frequency domain analysis. A Matlab program was written to process all the measurements. HR and HRV can be exported as an excel file (Fig.5.7).

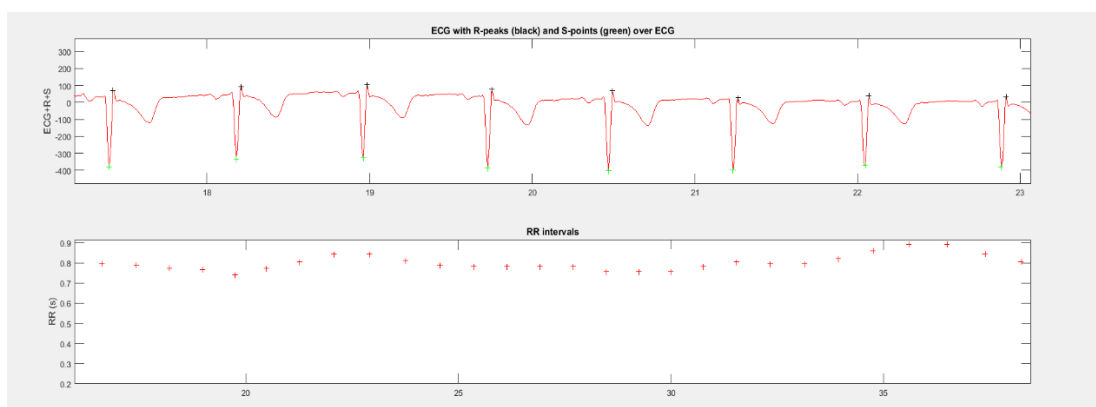


Fig.5.7 ECG data extrapolation

According with HRV measurements defined by Malik et al. [8] and Vollmer [9], the SDNN (standard deviation of the successive RR), (1) and the RMSSD (root mean square of the

sum of successive differences between adjacent RR intervals), (2), time domain parameters were calculated.

$$SDNN = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (RR_i - \overline{RR})^2} \quad (1)$$

$$RMSSD = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (RR_{i+1} - RR_i)^2} \quad (2)$$

SDNN reflects all the cyclic components (i.e., short-term and long-term) that are responsible for variability in the period of recording.

Normally it is calculated over a 24 h period. As the period of monitoring decreases, SDNN estimates shorter cycle lengths. It should also be noted that the total variance of HRV increases with the length of analyzed recording [10]. RMSSD is commonly used as an indicator of vagally (Vagus Nerve) mediated cardiac control which captures respiratory sinus arrhythmia (RSA), the frequent changes in heart rate occurring in response to respiration [11].

Frequency domain analysis describes high and low frequency rates of variability changes, corresponding to the activity of ANS.

The high frequency power (HF), (0.15-0.4 Hz), is a marker of parasympathetic activity; the low frequency power (LF), (0.04-0.15 Hz) is a marker of parasympathetic and sympathetic activity. Very low frequency power (VLF) (0.003–0.04 Hz), equates to rhythms or modulations with periods that occur between 25 and 300 seconds. Although all 24-hour clinical measurement of HRV reflecting low HRV are linked with increased risk of adverse outcomes, the VLF band has stronger associations with all-cause mortality than LF and HF band. Low VLF power has been shown to be associated with arrhythmic death and PTSD.

The ultra-low frequency component (ULF), (≤ 0.003 Hz), can also be used to analyse the sequence of NN intervals in the entire 24-hour period. The result then includes an ultra-low frequency component (ULF), in addition to VLF, LF and HF components (Fig 5.8).

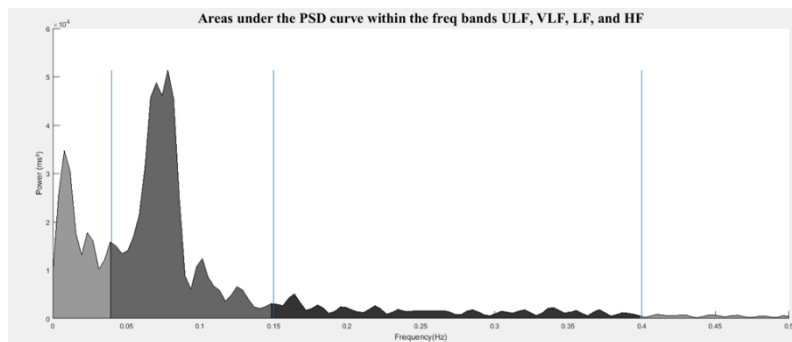


Fig.5.8 Relative power spectra density

The ratio LF/HF (3) represents the sympatho/vagal balance or the sympathetic modulations (Fig.5.9).

$$\frac{LF}{HF} = \frac{\int_{0.04 Hz}^{0.15 Hz} F(\lambda) d\lambda}{\int_{0.15 Hz}^{0.40 Hz} F(\lambda) d\lambda} \quad (3)$$

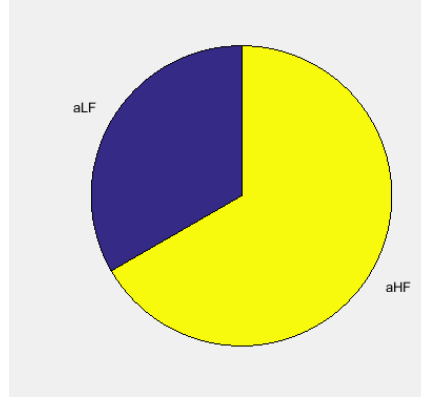


Fig.5.9 Ratio LF/HF

Endurance and training induces an elevated parasympathetic modulation over 24-hour recording period (higher RMSDD and HF and lower LF/HF ratio) [12].

Minassian et al. [13] investigated the association of pre-deployment heart rate variability with risk of post-deployment posttraumatic stress disorder in active-duty marines. After accounting for deployment-related combat exposure, lower HRV before deployment as measured by an increased low-frequency (LF) to high-frequency (HF) ratio of HRV was associated with risk of PTSD diagnosis after deployment. The prevalence of post-deployment PTSD was higher in participants with high pre-deployment LF/HF ratios (15.8% [6 of 38 participants]) compared with participants who did not have high LF/HF ratios. O' Donnell et al. [14] investigated the effects of stressful military training on physiological, and cognitive functioning of armed forces members. They have found that those individuals who have better stress tolerance exhibit significantly different patterns of heart rate variability, both at baseline (one week prior to stress exposure) and during stress exposure (to be reviewed later). These baseline differences in heart rate variability are predictive of actual military and cognitive neuropsychological test performance scores assessed during and after stress exposure. Heart rate variability (HRV) indexes both peripheral and central activity of the 5 parasympathetic and sympathetic nervous systems. Mäntysaari et al. [15] evaluated the usefulness of heart rate variability (HRV) for monitoring the soldiers' physiological status during a 19-day ranger training operation. HRV analysis based on data collection made in the field by the soldiers themselves is not a robust enough method to monitor the physiological status of soldiers. Both the time and frequency domain analysis of HRV require an ECG recording that is quite free from artefacts and technical disturbance, and with a stable baseline. These requirements are difficult to be met in the field because the soldier should be able to rest in calm conditions at least for 5 minutes in order to obtain acceptable HRV data. It seems to us that the studies of HRV analysis for monitoring the physiological condition of a soldier should be directed to more technical tasks, in which the optimal conditions for data collection can be achieved.

Another method is the geometrical one, based on a histogram of RR intervals with a bin size of 1/128 sec. The HRV triangular index is given by the most frequent value X (mode) with the absolute frequency k [9]:

$$\text{HRV triangular index} = n/k$$

A triangular interpolation of the discrete distribution of RR intervals (histogram counts), (Fig. 5.10) is used for the TINN measures:

$$\text{TINN} = M - N$$

where M and N are the vertices of the triangular function T , with $T(t) = 0$ for $t \leq N$ and $t \geq M$. The modal bin is identical to the sample distribution $T(X) = k$. T receives the values of a linear function by connecting $(N, 0)$ with (X, k) and (X, k) with $(M, 0)$. The triangular function with the best fit to the sample distribution defines M and M .

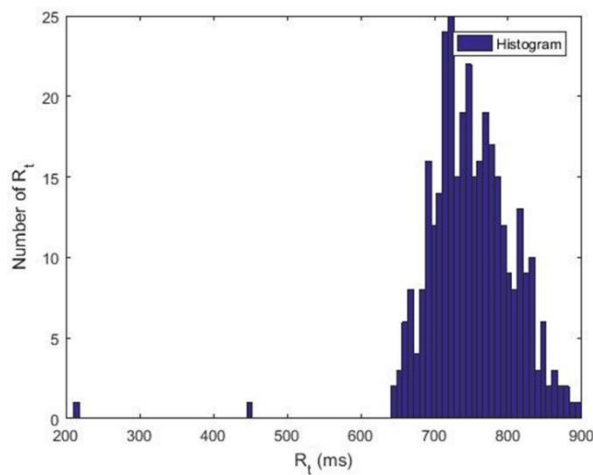


Fig.5.10 Histogram

HRV can be also measured using the return map of RR intervals “Poincaré plot” (Fig. 5.11) as ratio of the standard deviation $SD2$ along the identity line ($RR_{i+1} = RR_i$) and the standard deviation $SD1$ along the perpendicular axis ($RR_{i+1} = -RR_i$) [9]. The $SD1$ is based on “short term HRV” while $SD2$ on the “long term HRV”.

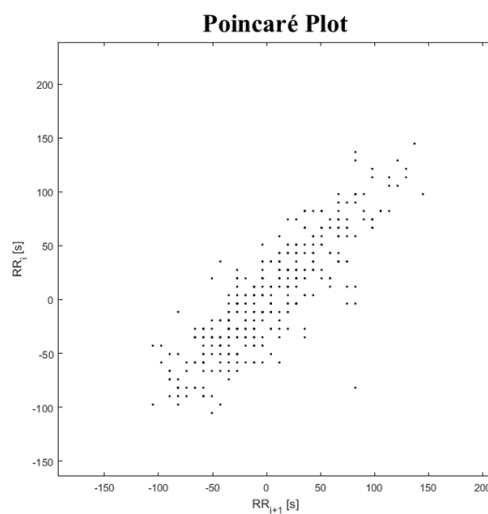


Fig.5.11 Poincaré Plot

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Conclusion and future work

6.1 General conclusion

The research presented in this work focused on the development of smart clothing for monitoring soldier's performance.

Starting from an anthropometric approach collected on 1615 Belgian soldier's "Total health Database", applying Drillis and Contini table we were able to calculate the segments of the upper body part. These dimensions allow to define the size of the smart shirt.

The next step was to evaluate the sensor body placement, the wearability and textile criteria of the smart cloth.

Different body position sensor placement was evaluated. The chest position was chosen as ideal position since it respects the unobtrusive placement.

The device is connected to the garments using a two-press stud and it sends the data acquired via Bluetooth.

The smart shirt, cut close to the body is made of base fabric (polyamide and elastane) and has two textrodes made by conductive materials positioned on the 10th rib at the distance of 15 cm between each other enabling transthoracic electrical biompedence measurements.

In term of prototyping, three smart shirts were realized.

The first one was inspired by body mapping of the sweating in male athletes. Qualitative study on a soldier population reveals that the shirt was not comfortable because of a limited movement at the armpit.

A second one, solved that limit thanks to the use of stretch fabric at the armpit permitting comfort and flexibility.

That feature allows us to extend the use of the smart shirt in sports such as climbing, rowing, archery, basketball, and volley-ball where a high range of motion at the armpit is requested.

The second prototype presents a hidden pocket able to transform the smart cloth by inserting a pad of D30 material for shock absorption and impact protection during activities like shooting.

Testing phase consisted in evaluating the two smart shirts starting with the biomechanical, ergonomical and physiological requirements of the end user during different tasks.

A Digital Human Modelling (DHM) of our soldier wearing the smart garment was created in Blender and used for the garment design and fit evaluation.

Thermal comfort was investigated using athermal imaging camera.

Comparing the first prototype with the second we saw a strong difference in temperature between the first and the second prototype. The second prototype revealed to be more thermophysiologicaly comfortable than the first. But, it presents the characteristic to become uncomfortable when immersed in the water.

Iterative studies on the co-design workflow permitted us to redefine the final functional garment realizing a third prototype which can be used for monitoring soldier's

performance in terms of training, injuries, and psychological status monitoring inside and outside the water.

Co -design workflow permitted to define material selection, the design, and its limits. Transparent bi-component silicon makes the electronics package able to maintain the Bluetooth connection through the package.

The three smart cloths are washable. But the electronic package realized at POLIMI is not waterproof. This gives a limit for the soldier who has not time to think in which environment he/she operates.

The monitor data can either be stored or immediately transferred to a tablet or smartphone giving a live feedback of the soldier.

In terms of real time Bluetooth data transmission operating at the standard 2.4 GHz had hard time penetrating the water for a distance of more than 100 mm between the wearable device and an external device (tablet or smartphone). To preserve the communication in real time, at long distances a repeater was ideated and attached to the back of the soldier.

Smart t-shirt monitoring capabilities can be extended from the lab to the field permitting a continuous physiological monitoring (HR and HRV) and the wearer's gesture detection.

Finall, the smart technology equipment is composed by:

- A wearable device (waterproof package) measuring and recording motion data (3D accelerations) and physiological data (heart rate variability).
- A smart shirt (long sleeves) with two textrodes embedded into the cloth. The new shirt presents a hidden pocket inserted on the right shoulder. This gives the possibility to transform the shirt inserting a pad of D30 material for shock absorption and impact protection during activities like shooting.
- A smart vest with two textrodes embedded into the cloth.
- A mobile app for real time processing and visualization in real time.

6.2 Research contributions and innovation

The main research contributions of this thesis are summarized as follows:

1) With respect to garment design, we studied breathable materials that combined can preserve comfort and fitting of the garment where it is needed.

Thanks to the collaboration with Moda Lab (POLIMI), we applied a new technique using adhesive bonding tape to enhance the look and the comfort of performance wear, outerwear, and lifestyle apparel. This tape replaces elastics and bulky sewn seams in performance wear and intimate wear.

2) A free 3D software, Blender, was used as a DHM tool to create a main parametric mannequin module and a fabric pattern module. Anthropometrical and biomechanical measurements from a motion tracking system and the smart shirt on a soldier, were integrated in a DHM Belgium Soldier avatar.

This DHM can be used to embed real-time representations of a live soldier in virtual environments.

3) In terms of electronic package design, new materials were used to design a waterproof electronics package enabling to monitor the wearer's performance in the water. We found a bi-component transparent silicon that can be used in the water to design a water-resistant device maintaining the Bluetooth transmission.

4) Regarding the connection, we developed a new concept able to maintain Bluetooth communication signal into the water. This allows to preserve the communication in real time between the electronic package and another device (smartphone, tablet, smartwatch) through the water and outside the water.

The Bluetooth low energy BTM 182, part of wearable device attached to the front of the shirt, communicates with a repeater contained in a waterproof package on the back of the soldier.

5) In terms of algorithm detection and processing, we developed a new assessment of Human Balance due to Recoil Destabilization using Smart Clothing. The smart shirt based on body-worn accelerometers (trunk accelerometers) was compared with posturographical by a pressure plate obtained during each shooting trial. The smart t-shirt revealed to be an innovative tool to assess human balance due to recoil destabilization. The new shirt presents a hidden pocket that contains a pad of D30 material for shock absorption and impact protection during activities like shooting. Quantitative questionnaire on soldiers revealed the effectiveness.

6) Heart rate variability measurements in time and in frequency domain were extrapolated through a MATLAB algorithm that works offline on time intervals between successive heartbeats from electrocardiographical (ECG) recording collected by two tetrodes embedded on the cloth. This represents a new assessment for the evaluation of soldier's physiological status in a non-intrusive and ecological method.

6.3 Research prospective

Further studies are necessary in the following domains to improve the current results:

1) In terms of garment design, new studies and acquisition protocols are necessary to evaluate the performance into the water.

Furthermore, we must understand if the signal detection in the water can be improved by a specific automatic calibration algorithm or if it is necessary to change the way in which it detects the start and the end of a session.

Also, the possibility to storage the data by on a SD card in the water should be investigated. In real time communication, we should study more AT commands between the wearable device and an external repeater (tablet or smartphone). We must improve the power management system. Such power management system can consist of flexible batteries or a solar panel providing continuously energy to the system.

Further experiments on a wide population are necessary to validate the device.

2) Regarding the digital human modelling tool, the mesh used came from a Mixamo library.

We suggest having a 3D human model created from a 3D body shape (mesh) of a Belgian soldier. This was not possible since we do not have a 3D body scanner or access to a 3D anthropometric database.

3) We would like to evaluate new physiological (respiration) and biomechanical (gait) measures and integrate them in sport and in rehabilitation protocols using the smart clothing.

6.4 Continuation of the presented research

The method studied in this thesis will be applied in a new Defence project.

The long-term concept is to provide a common wearable biomedical sensor system that enables the Defense organizations to improve military performance safeguarding the health and security of its personnel during training and operations.

There is a huge interest in the physical rehabilitation of the military patient suffering from musculoskeletal injuries. The actual physical assessment of the patient with cervical, back, or lower limb impairments is already of high quality but lacks functional high impact and speed movement analysis. This technology together with new healthcare algorithms and subsequent rehabilitation protocols would permit more efficient rehabilitation.

Starting from this assumption, a Defence Project, “Monitoring and Modeling Physical Function and Performance in Military Rehabilitation” was submitted and approved. It will start on 2018 for a duration of four years.

The purpose of this project is to apply the developed technology into a clinical setting and to develop mathematical algorithms which could be applied in this setting to develop rehabilitation protocols. The originality stands in the combination of two disciplines (rehabilitation & mathematics) which are extremely different but where complementarity will be the lever to a new approach of the complexity of rehabilitation sciences.

This project is an international collaboration between the Belgian Royal Military Academy (Dept. Mathematics), the Military Hospital Queen Astrid (Belgium) and the Politecnico di Milano (Design Dept.)

Decoding borders in smart clothing

"Borders may divide us, but, paradoxically, they're also the places where we're nearest to one another."

Ken Jennings

The border represents a line dividing parts, a defined limit. According to the Oxford dictionary, 'border' is "the edge or boundary of something, or the part near it". Being them physical or virtual, material or metaphoric, borders are liminal spaces where two or more parts meet each other. In this sense, a bordering line is a place where divisions become opportunities of encounter.

According to this perspective, there are different ways of decoding borders through research in design. We point out three ways of dealing with borders: extending, passing through and blurring. Each approach assumes borders are limits but can provide opportunities to foster a mutual exchange between the parts they divide.

We used the term "passing through" to define a new definition of "passing through the fabric".

To pass through the borders, the electronics and the textile create a connection between two areas.

Definition of "passing through" is:

1) Moving from one area (A) to another (B), creating a connection between these two or more areas. The border is remaining. But our action is affecting its form.

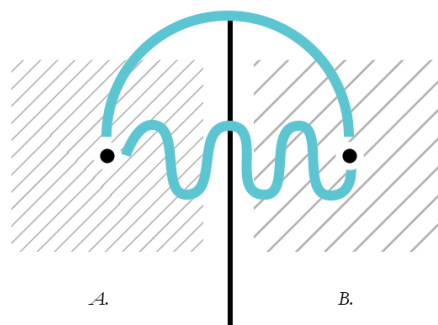


Fig.A.1 Passing through "A to B"

The interaction of the two borders, the electronics and the textile, opens new frontiers (a line of the borders) in the human factor fields.

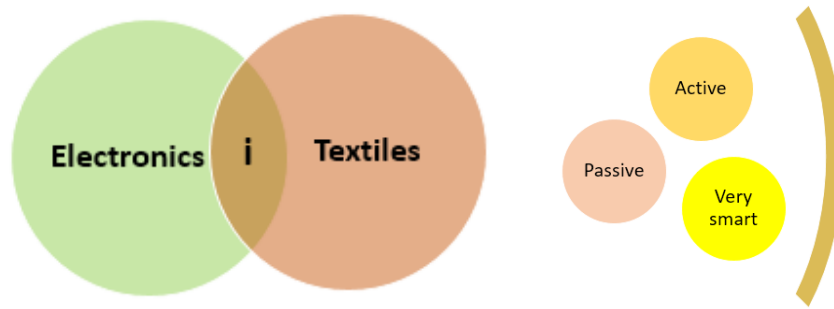


Fig.A.2 Intelligent textile fusion and differentiation

The interaction can be active, passive and very smart.

According to the manner of reaction, they can be divided into passive smart, active smart and very smart materials:

- Passive smart materials can only sense the environmental conditions or stimuli; they are sensors (optic fibres, conductive materials, thermocouples).
- Active smart materials will sense and react to the condition or stimuli. Besides the sensor function, they also have actuation characteristics. They can be divided in two: type one (chromatic materials, shape memory materials, phase change materials, hydrogels and membranes) and type two (luminescent materials, photovoltaics and electric textile).
- Very smart materials can sense, react, and adapt themselves accordingly (space suits, thermos-regulating clothing and health monitoring apparel). An even higher level of intelligence can be achieved from those intelligent materials and structures capable of responding or activated to perform a function in a manual or pre-programmed manner.