ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

DESIGN OF NEUROMUSCULAR ELECTRICAL STIMULATION DEVICE BASED ON SILITEX TAPE INTEGRATION

M.Sc. THESIS

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Department of Textile Engineering

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

SİLİTEX BANT ENTEGRASYONUNA DAYALI NÖROMUSKÜLER ELEKTRONİK STİMÜLASYON CİHAZI TASARIMI

YÜKSEK LİSANS TEZİ

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Sinem KAHVECI, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 503161830, successfully defended the thesis entitled "DESIGN OF NEUROMUSCULAR ELECTRICAL STIMULATION DEVICE BASED ON SILITEX TAPE INTEGRATION", which she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my family and my friends,

FOREWORD

I would like to express my special thanks of gratitude to my instructor Prof. Dr. Bulent Ozipek for his guidance and constant supervision as well as for providing necessary information regarding the project and also for his support in completing my project. Also, i would like to thank Mr. Yavuz Agaoglu from Teksel Textile, Istanbul company, Mr. Sven Bohmer from Statex, Germany company and Mr. Tom Kim from Samsung Knitting Needle, South Korea company for special effort and providing every material for my project. Also, I would like to thank my volunteers for their kind co-operation in my experimental work. I would like to thank my employer and my colleagues from my business life for understanding me and for providing time to my project. I would like to express my special gratitude and thanks to ITU and Marmara University Textile Laboratory managers for giving me such attention and time. I would like to express my special thanks to my family and my best friends who have always supported me in this tough period.

June 2019

Sinem KAHVECI
(Textile Engineer)

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ABBREVIATIONS

NMES **:** Neuromuscular Electrical Stimulation
EMG **:** Electromyography
App **:** Appendix

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DESIGN OF NEUROMUSCULAR ELECTRICAL STIMULATION DEVICE BASED ON SILITEX TAPE INTEGRATION

SUMMARY

Nowadays, electrical stimulation devices continue their development with different designs and technologies. This type of wearable devices provide extra movement to muscles by the effect of electrical force, while supporting muscle formation, cure occured pain due to continuous stagnation of muscles are expected. The aim of this study is to design a suitable neuromuscular electrical stimulation device for muscle supporting by integrating Silitex fabric included special silver conductive material onto the commercial knitted fabric. The device should be evaluated for ease of movement, easy portability and convenience.

Smart garments are widely used in medical and sport industry to heal people in need of treatment or strengthen muscles of people engaged in sports. The electrically conductive tapes (Silitex) are added to wearable products to stimulate the muscles. Thus, extra force is given to the muscles to provide more movement, therefore, more stimulated muscle begins to strengthen more than non-stimulated during the same period. The muscle strengthening and healing technique with electrical force was first used in medical fields such as spinal cord treatment, injuries of fractures in the body, and rehabilitation.

The effect of electrical force transmitted by Silitex tapes integrated onto the fabric on muscle performance was investigated in this study. For this purpose, Silitex tapes with conductive properties were prepared and integrated with the help of heat on the fabric. It was applied on the muscle and the changes between the muscle activation before and after the application of Silitex tapes were measured.

Neuromuscular electro stimulation devices are generally used in medical and sports industries. In medical fields, devices are used in two broad categories: therapeutic and functional. When muscles are not in use, strength of them weakened over time. In the therapeutic methods, strength is given to muscle with the help of electrical force. Functional electrical stimulation may change destroyed nerve pathways by electrical stimulation for helping to functional movement. So, NMES devices are

generally preferred when protecting of muscles from potential injuries or to increase muscle strength.

The aim of this study is to design and develop a portable product that can be applied easily to every region of the body, increase muscle strength and durability, massage the areas with a feeling of pain, provide physiological relaxation, and conduct electrical energy on the muscle with conductive tape integration.

SİLİTEX BANT ENTEGRASYONUNA DAYALI NÖROMUSKÜLER ELEKTRİKSEL STİMÜLASYON CİHAZI TASARIMI

ÖZET

Günümüzde elektriksel stimülasyon cihazları, farklı tasarım ve teknolojilerle gelişimini sürdürmektedir. Bu tip giyilebilir cihazların elektrik kuvveti etkisiyle kaslara ekstra hareket sağlaması, kas oluşumunu desteklemekle birlikte, kasın sürekli durgun olmasından dolayı meydana gelebilecek ağrı ve acıları da tedavi edici olması beklenmektedir. Bu çalışmanın amacı, elektriksel iletkenliği olan gümüş içerikli özel Silitex kumaş yapısını örme kumaşa entegre ederek her kullanıcıya uygun bir kas destekleyici nöromusküler elektriksel stimülasyon cihazı tasarlamaktır. Hareket kolaylığı, kolay taşınabilirlik ve rahatlık açısından cihaz değerlendirilmelidir.

Akıllı giysiler, medikal ve spor endüstrisinde, tedaviye ihtiyacı olan insanlar tarafından iyileşmek veya spor yapan kişiler tarafından kasları güçlendirmek için yaygın olarak kullanılmaktadır. Elektriksel olarak iletken bantlar (Silitex), kasları uyarmak için giyilebilir ürünlere eklenir. Böylece, daha fazla hareket sağlamak için kaslara ekstra güç verilir, bu nedenle, daha uyarılmış kas, aynı süreçte uyarılmayandan daha fazla güçlenmeye başlar. Elektrik kuvveti ile kas güçlendirme ve iyileştirme tekniği ilk olarak omurilik tedavisi, vücuttaki kırıklar ve rehabilitasyon gibi tıbbi alanlarda kullanılmıştır.

Bu çalışmada, Silitex bantların kumaşa entegre ettiği elektrik kuvvetinin kas performansı üzerindeki etkisi bu çalışmada incelenmiştir. Bu amaçla, iletken özelliklere sahip Silitex bantlar hazırlanır ve kumaş üzerindeki ısı yardımıyla entegre edilir. Silitex bantlarının uygulanmasından önce ve sonra kas aktivasyonu değişimleri gözlemlenir.

Nöromüsküler elektro stimülasyon cihazları genellikle tıp ve spor endüstrisinde kullanılır. Tıbbi alanlarda, cihazlar iki geniş kategoride kullanılır: terapötik ve fonksiyonel. Kaslar kullanılmadığında, zamanla kuvvetleri zayıflar. Terapötik yöntemlerde, elektrik kuvveti yardımıyla kaslara kuvvet verilir. Fonksiyonel elektrik stimülasyonu, fonksiyonel harekete yardımcı olmak için elektrik stimülasyonuyla

tahrip olmuş sinir yollarını değiştirmeye çalışır. Bu nedenle, NMES cihazları genellikle kasları potansiyel yaralanmalardan korumak veya kas gücünü artırmak için tercih edilir.

Her kas motor nöronları tarafından kontrol edilen kas liflerini içerir. Bu nöronlar biyoelektrik sinyalleri merkezi sinir sisteminden ilgili kaslara iletir. Kaslar gergin olduklarında biyoelektrik sinyaller oluşturur. EMG, hareket halindeki kasların biyoelektrik aktivitesini ölçen bir cihazdır. Elektromiyografi, biyoelektrik kas dalgalarının voltajlarını kaydeder ve ardından bunları sayısal değerlere dönüştürür. Kasın kasılması ne kadar güçlüyse, ekranda görüntülenen elektriksel aktivite değeri de o kadar yüksek olur. Bu çalışmada, sinyaller eMotion sEMG (yüzey EMG) tarafından 4 sensörle (16 g / sensör) toplanmıştır. Bu sensörlerin her biri anot (+), katot (-) ve toprak olarak adlandırılan 3 elektrot içerir. Sensörler kişinin cildine yerleştirilir, anot ve katot kasın üzerine yerleştirilir ve zemin elektrodu onlardan biraz uzağa yerleştirilir.

Bu pilot çalışmada kullanılan deney protokolü standart iki farklı koşulda insan deneklerden EMG sinyallerinin alınmasıydı: Silitex bantlı bir NMES giyerken ve hareket halindeyken, Silitex bantlı bir NMES giyerken ve hareketsiz pozisyonda. Toplanan EMG sinyalleri 100 bpm'de bir metronomla senkronize edildi (dakikada atım). 5 gönüllü insan denek, metronom ile toplam 20 saniye boyunca iki pozisyonu aldı.

Veri toplamada dört kanallı kablosuz bir EMG cihazı kullanılmıştır. Her kanal insan vücudundaki soleus kasına bağlandı. EMG ekipmanıyla birlikte gelen kayışlar kullanılarak her bir kas grubuna üç elektrot (pozitif, negatif ve toprak) yerleştirildi. Elektrotları yerleştirmeden önce her bireyin cildi EMG ekipman kılavuzunda belirtildiği şekilde temizlendi.

Ölçümler beş farklı kişinin Soleus kası üzerinde yapıldı. Bu ölçümlerin RMS değerleri EMG analiz programı MegaWin ile hesaplandı. Her kişi için hesaplanan ölçümlerin ortalama değerleri hesaplandı.

20 gönüllü psikolojik algı deneylerine katıldı. Gönüllüler, deneylerden sonra anket yardımı ile duygularını paylaştı. Anketin amacı gönüllülerin algılarını karşılaştırmaktı. Yaşları, kiloları ve boyları gibi özellikleri deneklere sorulmuş, ayrıca anket tasarlanan NMES cihazının insan denekleri üzerine fizyolojik-psikolojik etkileri ve estetik görünümün etkisi hakkında farklı sorular içermekteydi.

Yaş ortalaması 39, ortalama boy ve kilo sırasıyla 162 ve 69 olan 10 kadın ve 10 erkek denekten oluşan anket sonucunda; çoğunluk cihazın estetik görünümünü beğendi. Gönüllülerin çoğu cihazı kullanırken acı hissetmedi ve ürün memnuniyeti çok yüksek.

Bu çalışmanın amacı, iletken bant entegrasyonu ile vücudun her bölgesine kolayca uygulanabilen, kas gücünü ve dayanıklılığını artıran, ağrı hissi veren bölgelere masaj yapan, fizyolojik gevşeme sağlayan, kas üzerine elektrik enerjisi ileten taşınabilir bir ürün tasarlayıp geliştirmekti.

Tüm sonuçlar ve yorumlar dikkate alındığında NMES cihazının kas güçlendirme ve yaralanma tedavisinde iyi sonuçlar verebileceği tespit edildi.

1. INTRODUCTION

Individuals spend 90% of their lives in contact with textile products, so clothing products and accessories are designed to be used in the most comfortable way.

1.1. Definition of Problem

Smart garments are widely used in medical and sport industry to heal people in need of treatment or strengthen muscles of people engaged in sports. The electrically conductive tapes (Silitex) are added to wearable products to stimulate the muscles. Thus, extra force is given to the muscles to provide more movement, therefore, more stimulated muscle begins to strengthen more than non-stimulated during the same period. The muscle strengthening and healing technique with electrical force was first used in medical fields such as spinal cord treatment, injuries of fractures in the body, and rehabilitation.

The effect of electrical force transmitted by Silitex tapes integrated onto the fabric on muscle performance was investigated in this study. For this purpose, Silitex tapes with conductive properties were prepared and integrated with the help of heat on the fabric. It was applied on the muscle and the changes between the muscle activation feelings before and after the application of Silitex tapes were measured.

One surface of the Silitex tape is covered with silver and the other is covered with plastic. The plastic surface of the Silitex structure applied on the fabric is designed to touch the body. In this way, the structure of Silitex keeps the silver between the fabric and plastic and ensures that the silver conductivity remains resistant. At the same time, the plastic part ensures that the product does not slip easily over the muscle where it is applied and fabric is not damaged in case of perspiration during movement.

Questionnaires were conducted with individuals using NMES product with Silitex band. The sensations in their bodies were recorded after applying 20 minutes of experimental protocol. NMES device was applied wrist, knee, waist, and ankle when the subjects stood motionless.

The NMES device with Silitex tapes was designed to stimulate muscle groups used during motionless position of body and during sport. EMG measurements of subjects wearing the NMES device, motionless position of muscle and motion position of them were recorded during a standardized protocol via a wireless surface EMG system. EMG signal was synchronized with a metronome and collected from subjects during protocol. The EMG signals retrieved from subjects using the NMES device, two different positions were compared to detect the effect of electrical forces on muscle activation.

1.2. Objectives

The aim of this study is to design and develop a portable product that can be applied easily to every region of the body, increase muscle strength and durability, massage the areas with a feeling of pain, provide physiological relaxation, and conduct electrical energy on the muscle with conductive tape integration.

1.3. Literature Review

1.3.1. Biomechanics of human body

Biomechanics of the human body help us to understand movement and performance. Biomechanics consists of two parts; kinetic and kinematics. Kinetic help us to comprehend the characteristics of movement.

Kinematics can be defined as the body's own movement without the influence of internal and external forces in the body. It deals with movements and positions of muscles, joints and parts of the body.

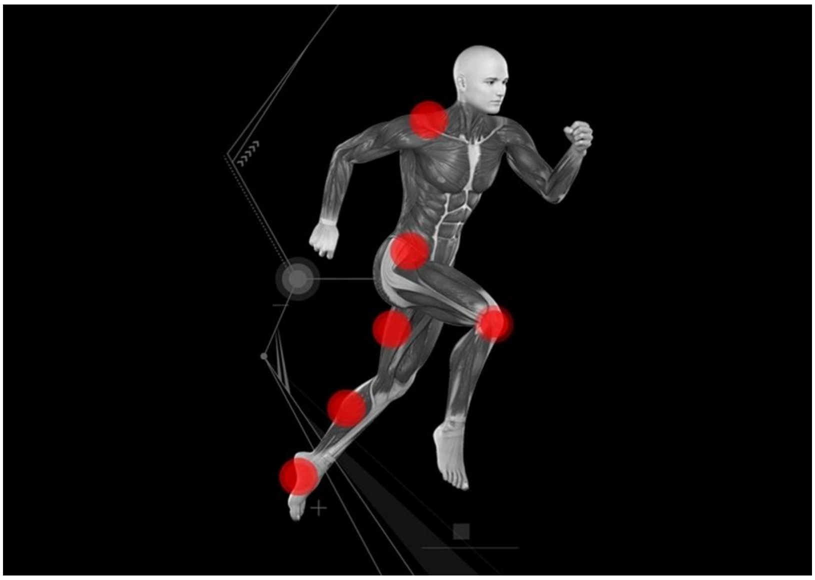

Figure 1.1: Biomechanics of human body.

Forces are applied as push and pull. A force can cause movement, stop movement or change the usual movement. The movement can also change the shape of the structure in which it is applied.

Contact forces consist of contact between two bodies. The forces of our feet in contact with the ground are examples of contact forces. In addition, there are field forces such as electric, magnetic and gravity that surround our body. The force of gravity, muscle forces and frictional force are the forces that are important for the human body and are related to body movement. Gravity and muscle strength cause the body to contraction and relaxation the tissues or organs.

The maximum force a muscle can exert depends on the cross-sectional area of the muscle and is specific to the structure of the muscle fibers. This maximum force per unit area ranges from 30 to 40 N / cm^2 [1].

1.3.2. Muscle physiology

The posture and movement of the body are controlled by the forces produced by the muscles. There are about 600 muscles in the human body, responsible for all movements from very fine movements in the face to the bloodstream, from speech to the heart. A muscle is attached to two different bones with tendons. Muscle, consists of a large number of fibers that can compress the cells when stimulated with signals from the brain. The representation of a bicep muscle, arm bones and forearm with an object in resting state can be seen in the figure below.

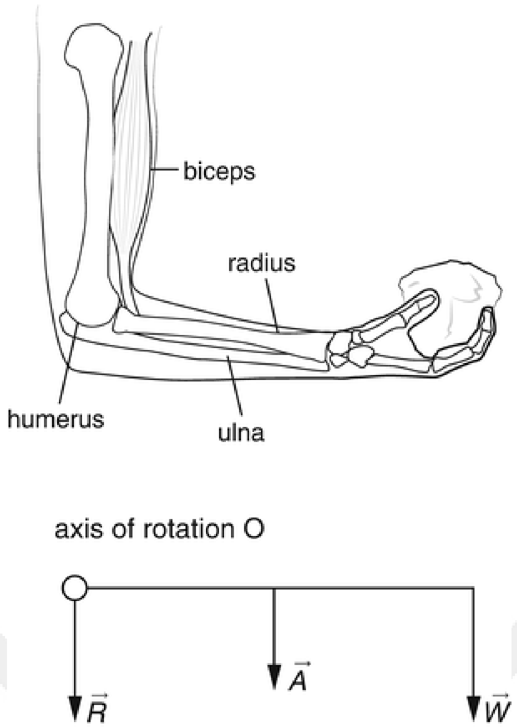

Figure 1.2: The arm muscle responds to the sum of all downward forces.

The sum of all downward forces is equivalent to the reaction force of the bicep muscle. In other words, against the downward forces, the bicep applies an equal amount of reaction force in the upward direction.

The force between the feet of a sitting person and the ground moves in opposite directions. Shoes apply force to the ground.

Figure 1.3: The force between the foot of a sitting person and the ground is opposite.

The pressure is related to the force applied on a body. P pressure is defined as the force per unit area applied perpendicular to a surface.

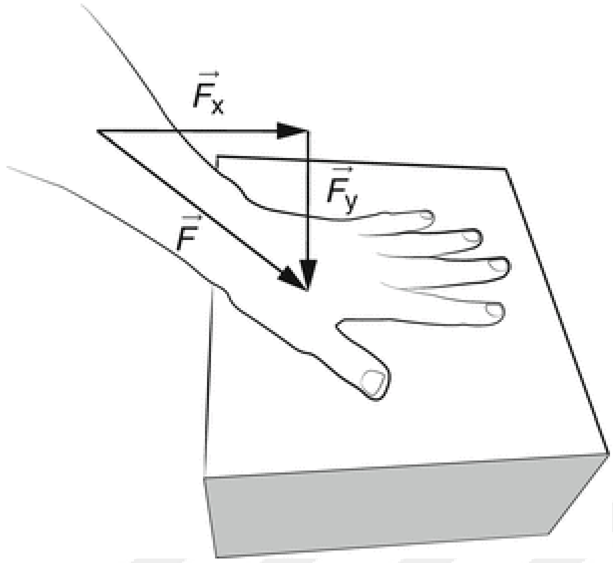

Figure 1.4: The F force applied to a block is divided into horizontal and vertical components.

According to the working principle of the muscles, each muscle operates in one working cycle. This cycle, which is built upon the muscles contracting and loosening, is necessary to complete the movement. If the muscles of the human body apply force, they can mobilize an object or change the movement of the objects. When the physiological movements of the muscle are examined, it is seen that the signals transmitted from the brain to the spinal cord are sent to the muscle via motor neurons and the stimulation of the muscle is realized. The muscle with the sensory neuron in the response is also sending a signal to the brain. Individuals often do strength training to increase muscle strength, and the increase in muscle strength positively affects the quality of life [2-3-4-5]. In addition to increasing muscle strength, quality of life and body health, positive effects have been reported in the treatment of cardiovascular diseases and the number of patients in hospitals has decreased [6-7].

Wrong posture of the body during the day, generally cause great forces responsible for low back pain. The forces acting on the hips during the walk are very large. Simple models are used to calculate the magnitude of forces. These calculations are guided by the static equilibrium values of the body.

One of the reasons for the wrong postures is the bending movement to brush the teeth in a high sink without knees twisting or to lift up a heavy object from the ground. If the knees are not bent, it is impossible not to bend the spine. The height of all the items around us is standard and the wrong designs which has uneven height of the closets, tables, chairs can cause back pain. Nowadays, many people are taking posture training to prevent pain caused by false posture.

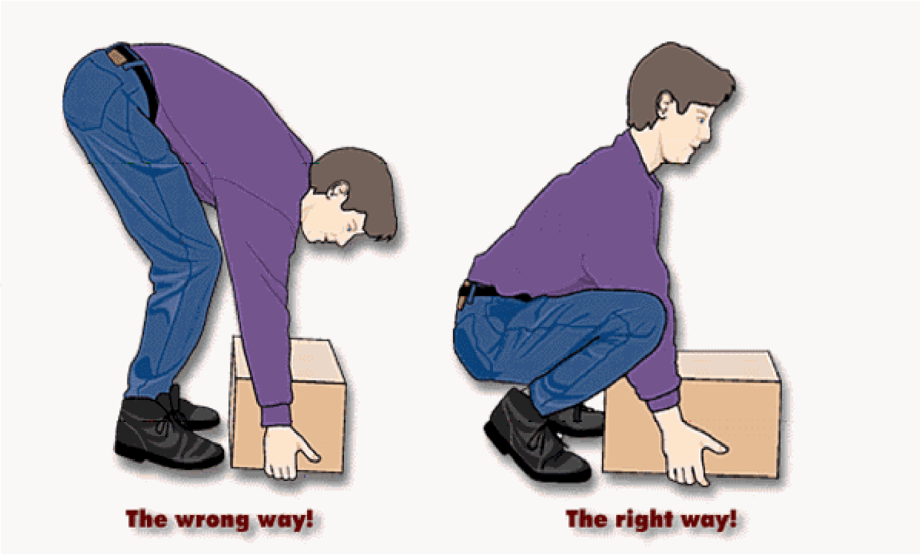

Figure 1.5: Wrong and right position of lifting up an objects.

In addition, the decrease in muscle density means that the mineral content in the body decreases, causing discomfort in the spinal cord as cardiovascular effects [7]. The loss of function in the older ages may adversely affect neural and cardiovascular systems. These changes lead to loss of muscle mass and strength, a decrease in aerobic capacity, and a deterioration of physical function [8]. In order to delay the degenerative processes in the aging muscle, it is necessary to exercise regularly [9]. Many older individuals cannot exercise due to their underlying diseases [10-11-12].

1.3.2.1. Muscle working and electricity connection

Using NMES devices can cause adverse effects as well as causing positive effects. These muscle strengths can also cause deformations of bodies that are usually not seen. Excessively high frequency can cause muscles to collapse, and too often low frequency may damage the muscles. In the literature, the muscle has been shown to become rapidly tired because of the high depolarization of the motor axons due to the high mobilization of muscle fibers [13-14-15-16].

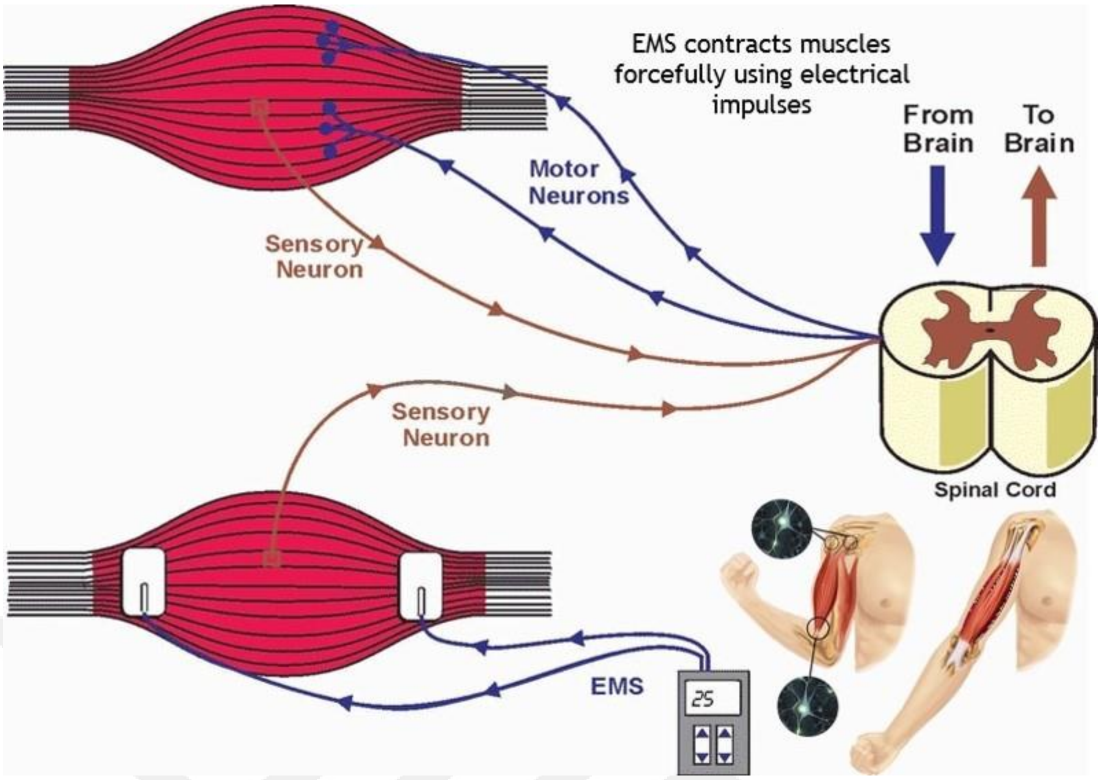

Figure 1.6: The effects of electrical forces on muscle contraction.

The application of tendon vibration during electrical stimulation helps to create permanent internal currents at the motor neuron level [17-18-19]. The positive effect of vibration is undeniable.

The reason why muscle stimulation is not frequently used in clinical cases is because there is not much research on its use in the literature [20].

Electromyography (EMG) and mechanomyograph (MMG) can be used to observe electrical and mechanical behaviors of muscle and oscillation of soft tissue and stimulation-contraction of muscle in order to figure out motor control working of neuromuscular system under varied compression circumstances. MMG is a device which is used for providing information about mechanical signal from muscle surface during contraction. EMG is a diagnostic device which is used for estimating and recording electrical activity of skeletal muscle. EMG records the changes in physiological condition of muscle fiber membranes as voltage. With surface electromyography (sEMG, surface EMG) these signals are registered noninvasively from skin surface by electrodes. Surface EMG is widely used to detect and analyze dynamic muscle activity of sportsmen. In surface electromyography applications for sports performance evaluation, it is important to conduct wireless electromyography

measurements without interfering movements of the sportsman. In evaluating sports performance, electromyography measures muscle activation. High muscle activation means an improvement in muscle performance within the same amount of exercise. On the other hand, low muscle activation in an equally maintained exercise performance means a similar exercise effect with a small amount of muscle use.
In this study, EMG was used in order to examine muscle activity. Surface electrodes were used for chosen muscle which is Soleus and electrodes were placed onto it.

Five subjects were tested for muscle group experiment: Soleus. The subjects whose Soleus muscles were electrically stimulated performed jumping jack movement for a period of 30 seconds and then stood motionless for another 30 seconds. During this 60-second period, their Soleus' response was measured with electrodes.

1.3.3. NMES garments

NMES controls the muscles contraction and relaxation by sending programmed stimulation to the body with the help of electrodes applied to the muscle [21]. NMES exercises have been shown to slow muscle weakening or even to increase muscle strength, which also positively affects skeletal muscle and improve physical health in people with spinal cord injuries [22-23-24-25].

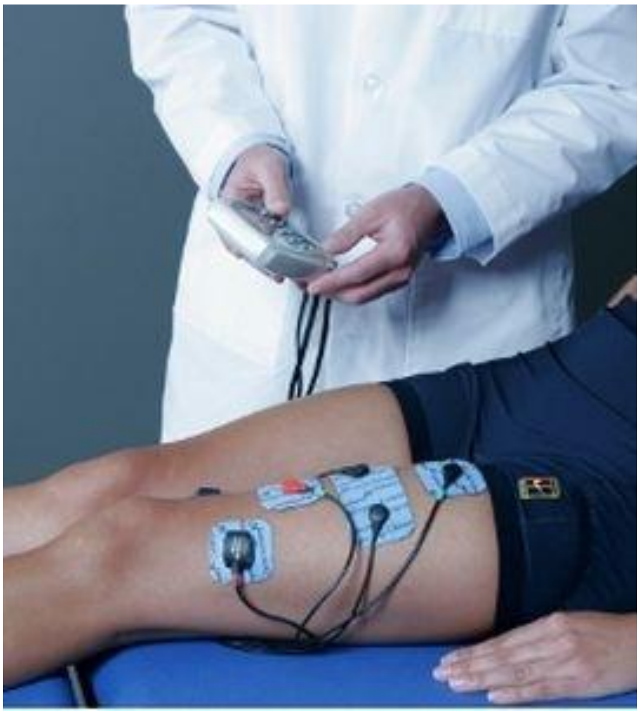

Figure 1.7: NMES device used in doctor's check.

Figure 1.8: Use of NMES device by person.

NMES is a program that does not need constant monitoring and is useful for people who do not like to make an effort for exercise, as it is an exercise method that everyone can easily choose in the desired environment [26].

Studies have shown that an individual with lung cancer increases physical performance by 44% after 20-60 minutes of NMES sessions [27]. In addition, a hybrid protocol was found to increase both aerobic capacity and strength at the same time in healthy elderly participants [28]. Additional technologies, such as NMES, have been used to improve neuromuscular and cardiovascular systems and help healthy or unhealthy people [29-30-31].

1.4. Constraints of Design Problem

One of the main problems of design was manufacturing of prototypes. Whole production process was performed by hand. The created device design required special focus during cutting and bonding of Silitex with adhesive material processes. Silitex was glued to the fabric by heat with double-sided adhesive. Swelling of Silitex was observed because of the formation of air gap when heat was applied.

The other limitation was lack of time for human subject tests. Some subjects feared the idea of applying electricity to the body. Therefore, they did not want to participate in the experiment.

Another constraint was placing the product in the body. Silitex part should be placed directly to the skin. In the prototype design, the integration of Silitex on the muscle was considered but the human body sizes changed from person to person, it was difficult to do.

1.5. Application Fields of Design

Neuromuscular electro stimulation devices are generally used in medical and sports industries. In medical fields, devices are used in two wide categories: therapeutic and functional. When the muscles are not in use, strength of them weakened over time. In the therapeutic methods, strength is gave to muscle by help of electrical force. Functional electrical stimulation try to change destroyed nerve pathways by electrical stimulation for helping to functional movement. Therefore, NMES devices are generally preferred to protect of muscles from potential injuries or to increase muscle strength.

1.6. Work-Time Table

The working program we implemented throughout the study is given below.

Work and Time Table																	
No:	**Work Description**	**Person/ Company**	**2019**														
			January			**February**				**March**				**April**			
Weeks		Weeks	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
1	**Antelope Smart Garment Experiment**	Sinem Kahveci															
2	**Material Supplying**	• Teksel Textile, Turkey • Statex, Germany															

		• Samsung Knitting Needle, South Korea
3	**Literature Review**	Sinem Kahveci
4	**Fabric Experiments**	Sinem Kahveci, ITU Laboratory
5	**Prototype Development**	Sinem Kahveci
6	**Prototype Experiments**	Sinem Kahveci
7	**Computer Analysis**	Sinem Kahveci

2. DESIGN METHODOLOGY

Production processes were divided into five main phases: development of design, cutting, pressing of Silitex, adding snaps and sewing.

Brainstorming with companies, idea generation, pattern making steps was followed in development of design processes. During the brainstorming phase, Antelope smart suit product from German brand Antelope Club, was examined in detail. After that development on the design of product were discussed together with Teksel Textile and Samsung Knitting Needle companies.

The fabric was cut according to design, Silitex was applied on fabric by ironing. After Silitex integration, snaps were added by manual snap press machine. In the next phase, overlock stitches was applied to edges of fabric for aesthetic appearance.

Figure 2.1: Silitex glued to fabric with interlining.

2.1. Definition of Design

Designed prototype includes two main parts: commercial flexible knitted fabric and Silitex fabric to conduct electricity. The purpose of the design is to improve the performance of the user in active or inactive. The most commonly used various muscles in our daily life are determined by theoretical (literature review) and practical (based on observations) studies.

Double plate, interlock polyester fabric with 2,817 g/dm^2 basis weight was used for the NMES device. Fabric has 2,817 g/dm^2 and final basis weight is 6,876 g/dm^2 after Silitex integration. Also, its air permeability and water vapor permeability properties are 559,8 l/m^2/s and 940,476 l/m^2/s respectively. 78% polyamide + 22% elastomer silver-plated knitted fabric that has one side coated with black conductive silicone Silitex was used for electrical conductivity.

Ideas for NMES device design were generated with brainstorming sessions by taking into consideration the muscle groups and commercial product designs. Silitex bands were prepared by hand cutting. The prepared bands were adhered to the fabric using commercial two-way interlining by using Rowenta Focus branded iron at third temperature level without stream for 1 hour. After the Silitex integration, the edges of the product were sewn with overlock stitching for aesthetic appearance. Then, in order to bond the booster, snaps were placed on the fabric at a suitable distance.

Figure 2.2: Designed NMES device.

Figure 2.3: Distances of snaps.

2.1.1. Function of design

The NMES device prototype was designed to stimulate the muscles so that they do not stay motionless for a long time or to give extra strength. The main purpose of the device is to improve user performance and prevent the body from potential injuries.

2.1.2. Criteria chosen for design evaluation

The prototype was created to fit easily to any area to be used on the muscles that will cause the most pain in the human body. Wrist, knee, waist, and ankle are the body areas that cause the most pain in people who work according to theoretical and practical studies results. This design can be used both for athletes and for treating diseases.

The electrical stimulation frequencies given to the muscles are variable. For the first 5 minutes the related muscle is stimulated at a constant frequency, stop for 3 seconds and continue for 5 seconds. It continues in the next 5 minutes, the waveform frequencies nonstop continues to increase and decrease. In the last 5 minutes, it continues for 5 seconds constant frequency and backs to waveform frequency for remaining minutes.

2.1.2.1. Muscles

The NMES devices on the market were examined and the muscle groups affected by these devices were taken into consideration when designing. Portable NMES device can be easily used on wrist, ankle, knees and waist areas. It were determined by employees and athletes.

Figure 2.4: Muscles of the human body.

According to the location of the muscles used actively, Silitex bands were placed on these regions to apply electricity on these muscle groups and to develop muscles.

2.1.2.2. Pattern effects

The placement of Silitex tapes was inspired by the design of the Antelope Smart Suit and products from the market. Also, the design size of the Antelope Smart Suit booster was minimized. The portable regional neuromuscular electrical stimulating device instead of suit is designed to eliminate electrical conductive cables.

Figure 2.5: Designed NMES device on carpal tunnel.

The suit was divided into pieces to reveal a portable product that could be used on every muscle structure. Silitex was applied as double band and give distance between them for flexibility to be used in the most painful joints such as knees and wrists.

2.2. Strengths and Weaknesses of Chosen Design

Applying of Silitex to fabric surface resulted in both weakness and strength of design. The first negative effect was about comfort properties of the designed device as reduced breathability value because of Silitex. As a solution of this problem, Silitex was applied in the form of thin bands, not in large pieces.

Second weakness of the chosen design was the device could not be attached properly to the body. In order to solve this problem, a long thin piece in the design was added to be wrapped to the body. The band was also supported by an extra tire support.

2.3. Solution Possibilities of Design Problem

One problem of the designed prototype was that the product could not fully fit to the muscle region of the user due to the different body features. As a solution, the Silitex dimensions were reduced to use high stretch property of the knitted fabric. Therefore, Silitex was applied as two thin long tapes instead of the whole fabric cover. The distance between the two Silitex tapes were applied to ease of use in the knee and elbow points.

3. EXPERIMENTAL WORK AND TEST RESULTS

Various mechanical, chemical and comfort tests were applied to the double jersey interlock knitted fabric used for prototyping designs before and after integrating Silitex fabric in order to examine changes.

3.1. Textile Experiments

Test specimens were taken from different fabric regions and the test specimens used different yarns direction according to the relevant test and standard. Sample shape, size and cutting differences were considered according to the relevant tests.

The test applications were performed in Istanbul Technical University, Textile Technologies Faculty and Design Physical and Chemical Test Laboratory. The laboratory ambient conditions were average temperature was 20 Celsius and the relative humidity was 65%.

3.1.1. Mechanical test results

3.1.1.1. Measurement of basis weight test and results

The samples with area 100 cm^2 were taken from five different zones from fabric were prepared by SDL ATLAS round shaped sample cutter.

Precisa XB 620M precision scale was used and calibrated before testing. Measurement of basis weight of samples was measured with the help of Precisa XB 620M precision scales. Each of samples was weighed separately and mean value was calculated with (m1+m2+m3+... +mk) / k equation.

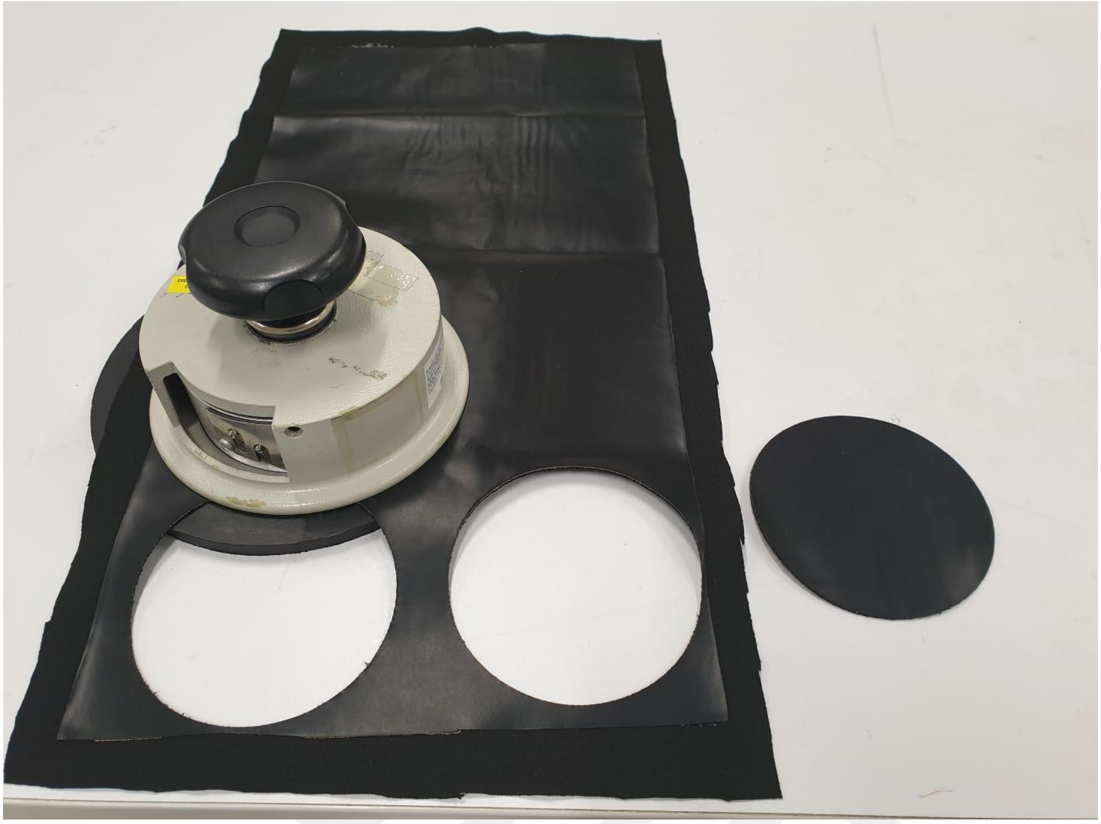

Figure 3.1: Measurement of basis weight.

Table 3.1: Measurement of basis weight test results.

Test Samples	Basis Weight of Fabric (g/dm^2)	Basis Weight of Addhesive Material (g/dm^2)	Basis Weight of Addhesive and Silitex Integrated Fabric (g/dm^2)
T1	2,871	0,831	6,839
T2	2,852	0,858	6,847
T3	2,811	0,826	6,867
T4	2,781	0,836	6,947
T5	2,772	0,84	6,879
Mean Value:	2,817	0,838	6,876

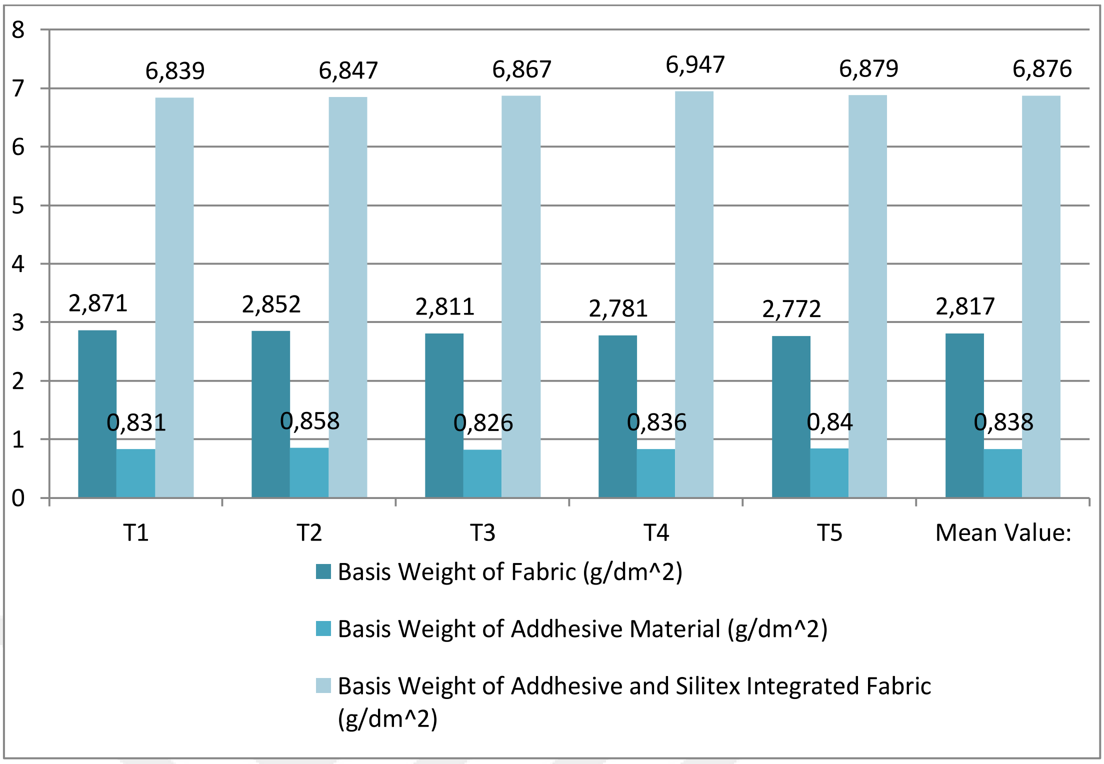

Figure 3.2: Comparison of basis weight.

Basis weight of T1 increases approximately 84.73%

Basis weight of T2 increases approximately 84.55%

Basis weight of T3 increases approximately 88.80%

Basis weight of T4 increases approximately 92.06%

Basis weight of T5 increases approximately 90.44%

Mean value of basis weight increases approximately **88.12%**

3.1.1.2. Number of threads per unit length test and results

For test samples, 2 cm different areas of the fabric were marked and yarns in marked areas were counted under the optical counting device loop and microscope. The alignments were counted for the number of stitches and loops was counted for the number of rows. The yarn counts on the two directions in the measuring range was identified. The number of yarns at 1 cm was calculated and the process was repeated five times for two directions.

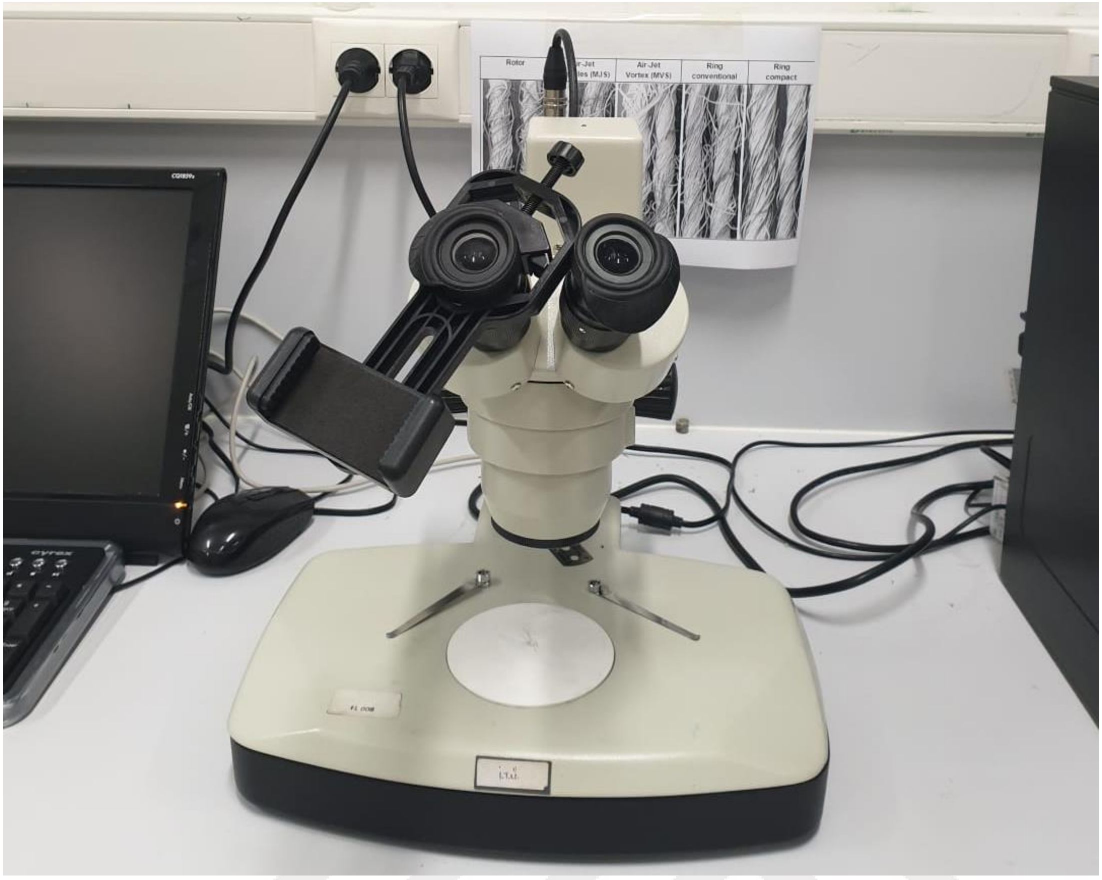

Figure 3.3: Optical counting device.

Table 3.2: Number of threads per unit length test results.

Test Samples	**Number of stitches /cm**	**Number of parallel rows /cm**
T1	15,5	22
T2	15	23
T3	16	22
T4	15	23,5
T5	14,5	24
Mean Value:	15,2	22,9

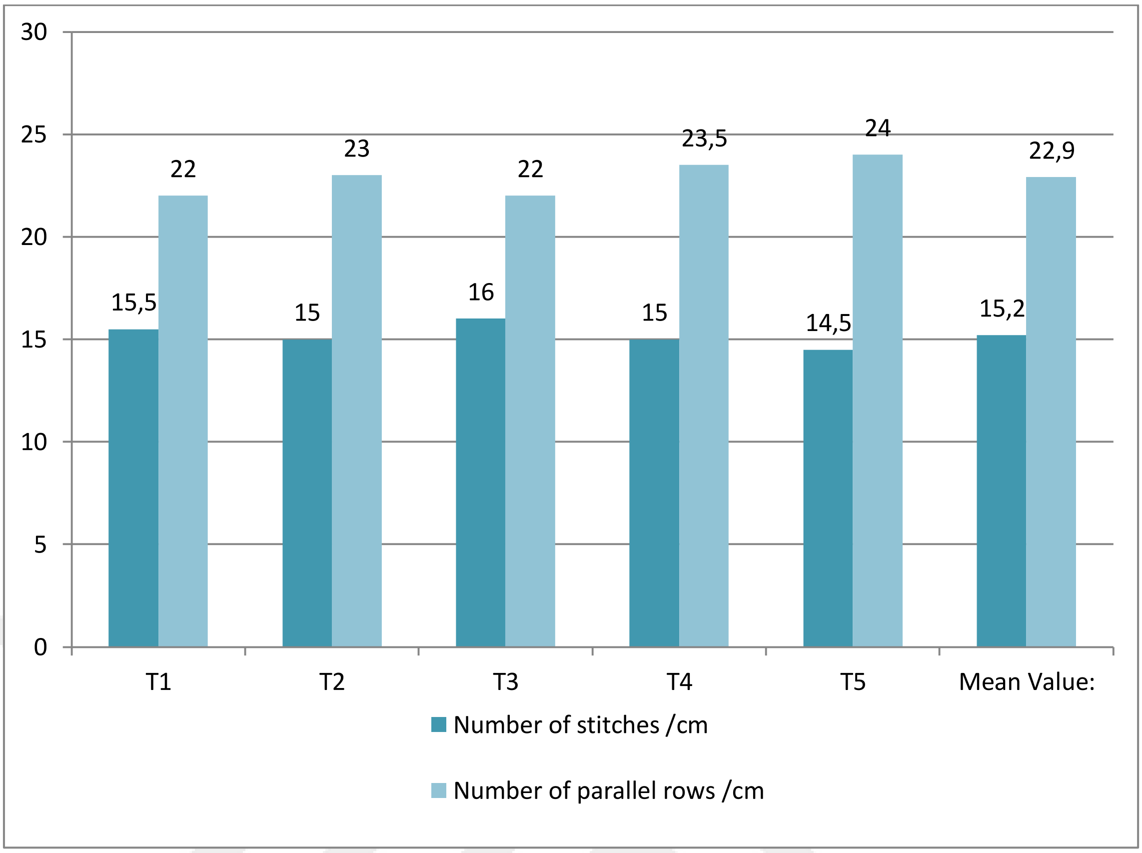

Figure 3.4: Number of yarns per unit length.

3.1.1.3. Fabric elongation and tensile strength test and results

Fabric elongation values were measured by James H.Heal by Titan-Universal Strength Tester. First samples were tested according to BS 4592-1992 standard. The first samples were tested according to BS 4592-1992 standard. Since the Silitex coating was rapidly separated from the fabric in the wrong direction, the measurements were not made appropriately. After that, the fabric tensile test for plastic coated fabrics is applied according to EN ISO 1421 standard Method 1.

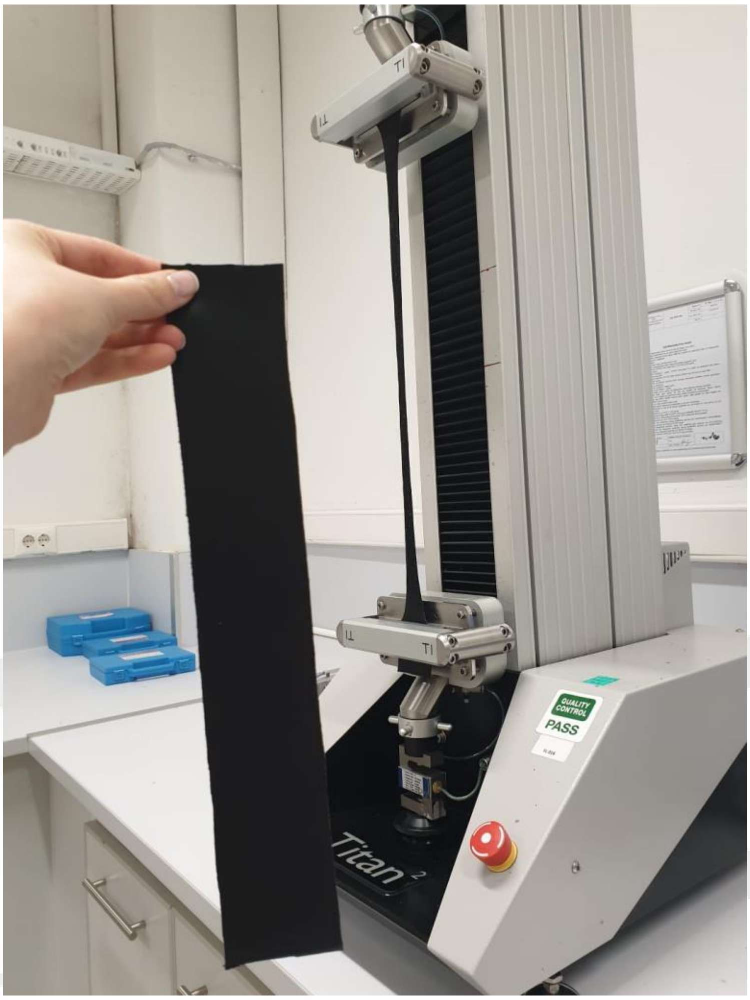

Figure 3.5: James H.Heal by Titan-Universal Strength Tester.

Figure 3.6: The specimens after fabric elongation and tensile strength test.

Test parameters:

Jaw Separation: 200mm

Rate of Extension: 100mm/min

Break Detection: 5%

Pretension: 5N

Maximum Load: 3000N

Load Cell S/N: 3000N

Table 3.3: Fabric elongation and tensile strength test results.

Warp Specimens	Max. Force	Extension	Weft Specimens	Max. Force	Extension
Mean	542.44N	197.40%	Mean	519.78N	148.45%
Maximum	595.06N	206.21%	Maximum	577.90N	155.25%
Minimum	475.95N	188.22%	Minimum	445.22N	140.50%
Standard Deviation	44.50N	6.82%	Standard Deviation	60.15N	7.17%
Coeff. of Var.	8.20%	3.46%	Coeff. of Var.	11.57%	4.83%

Fabric elongation and tensile strength of specimens under increasing force were shown graphs below.

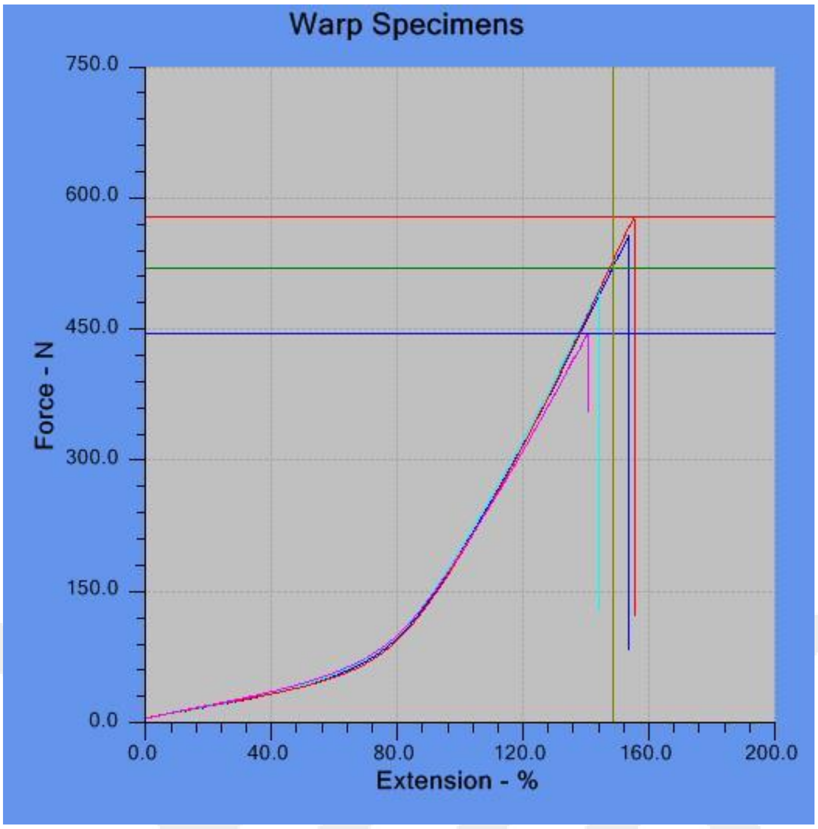

Figure 3.7 : Elongation values of warp specimens.

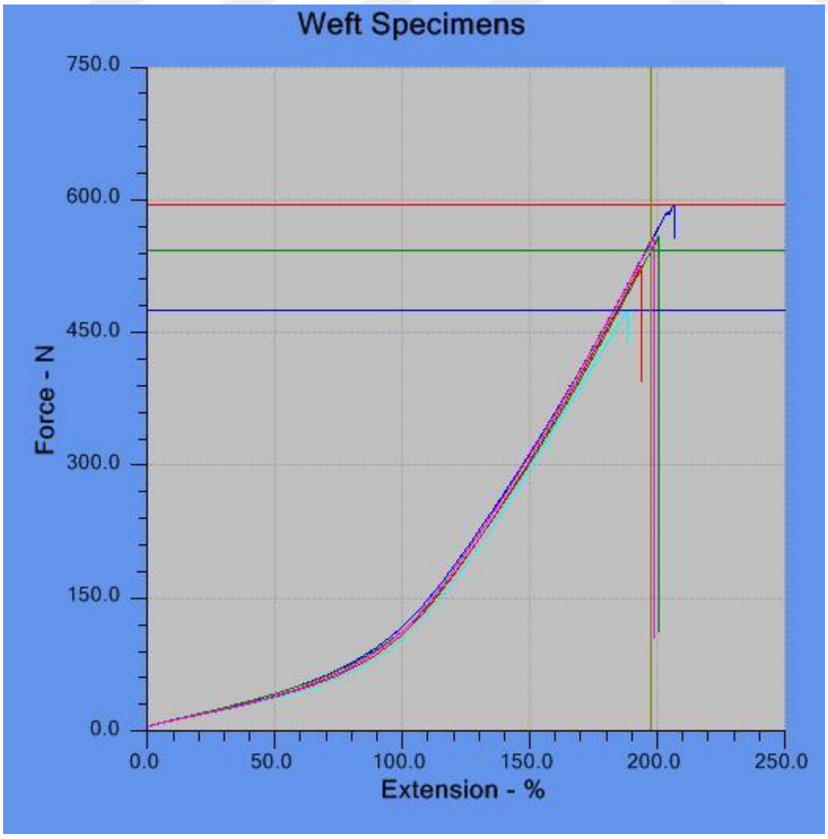

Figure 3.8 : Elongation values of weft specimens.

At the end of the experiment, it was observed that the fabric had high elongation and tensile strength in both directions.

3.1.1.4. Bursting strength test and results

Bursting strengths values of samples were measured by bursting strength device.

Test Standard: The test were applied knitted fabric, and Silitex integrated fabric. TS 393 EN ISO 13938-1 test standard conditiıons were used. The samples were conditioned in the laboratory before the test. The pressure was applied to fabric until it was exploded by the device. The bursting height, time and pressure values in kPa were recorded. Test was repeated in different zones of fabric for 5 times. The test is applied only knitted fabric according to standard.

Figure 3.9: Bursting strength device.

Table 3.4: Bursting strength test results.

Test Samples	Bursting time (s)	Bursting Strength (kg.force/cm^2)
T1	13,45	18,75
T2	13,50	18,25
T3	13,19	17,50
T4	13,56	18,95
T5	13,40	17,65
Mean Value:	13,42	18,22

After the Silitex was integrated in the fabric, the burst strength of the fabric could not be measured because the knitted fabric was treated like a woven fabric after being placed in Silitex and no result could be obtained.

3.1.1.5. Tear strength test and results

The tongued (double-tear) tear strength test for rubber or plastic coated fabrics is applied according to TS EN ISO 4674-1 standard Method A.

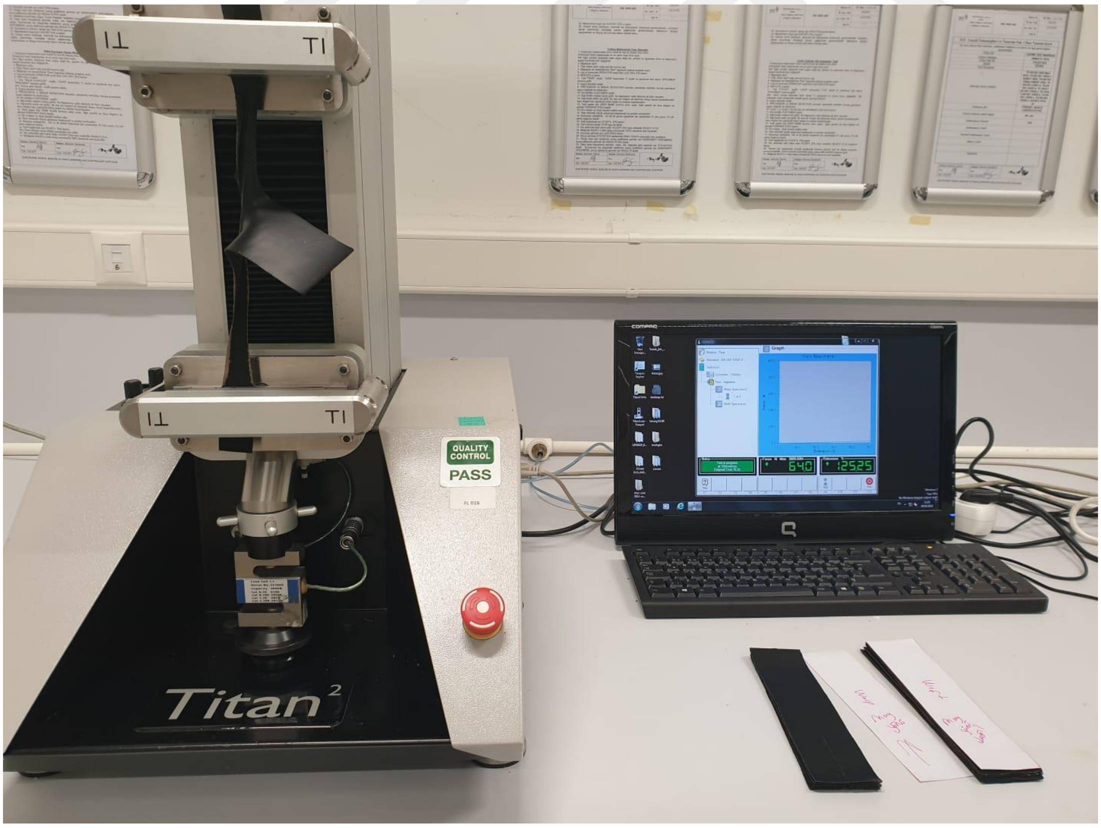

Figure 3.10: Tear strength test device and software.

Figure 3.11: The specimens after tear strength test.

Figure 3.12: Close appearance of specimen's tear.

Test parameters:

Jaw Separation: 100mm

Rate of Extension: 100mm/min

Break Detection: 0%

Pretension: 0%

Load Cell S/N: 3000N

Table 3.5: Tear strength of warp specimens and test result.

Results - Warp Specimens	Mean Peak Force (N)	Maximum Peak Force (N)	Observations
1	105.84	154.00	first the knitted fabric is broken.
2	116.50	142.45	first the knitted fabric is broken.
3	83.66	131.58	first the knitted fabric is broken.
Mean	102	142.68	
Maximum	116.50	154.00	
Minimum	83.66	131.58	
Std. Dev.	16.75	11.21	
Coeff.of Var.	16.42%	7.86%	

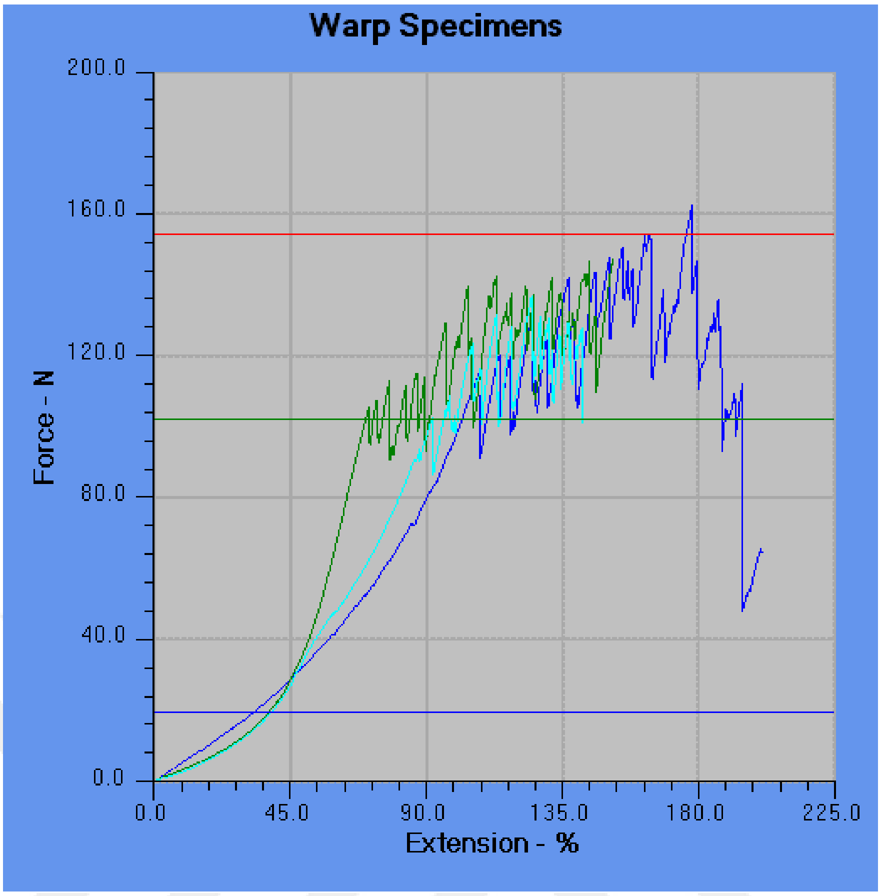

Figure 3.13 : Tear strengths of warp specimens.

Table 3.6: Tear strength of weft specimens and test results.

Results - Weft Specimens	Mean Peak Force (N)	Maximum Peak Force (N)	Observations
1	93.33	130.86	first Silitex is broken.
2	60.86	116.16	Silitex is starting to break.
3	111.56	147.53	Silitex was torn in the opposite direction.
Mean	88.58	131.52	
Maximum	111.56	147.53	
Minimum	60.86	116.16	
Std. Dev.	25.68	15.70	
Coeff.of Var.	28.99%	11.93%	

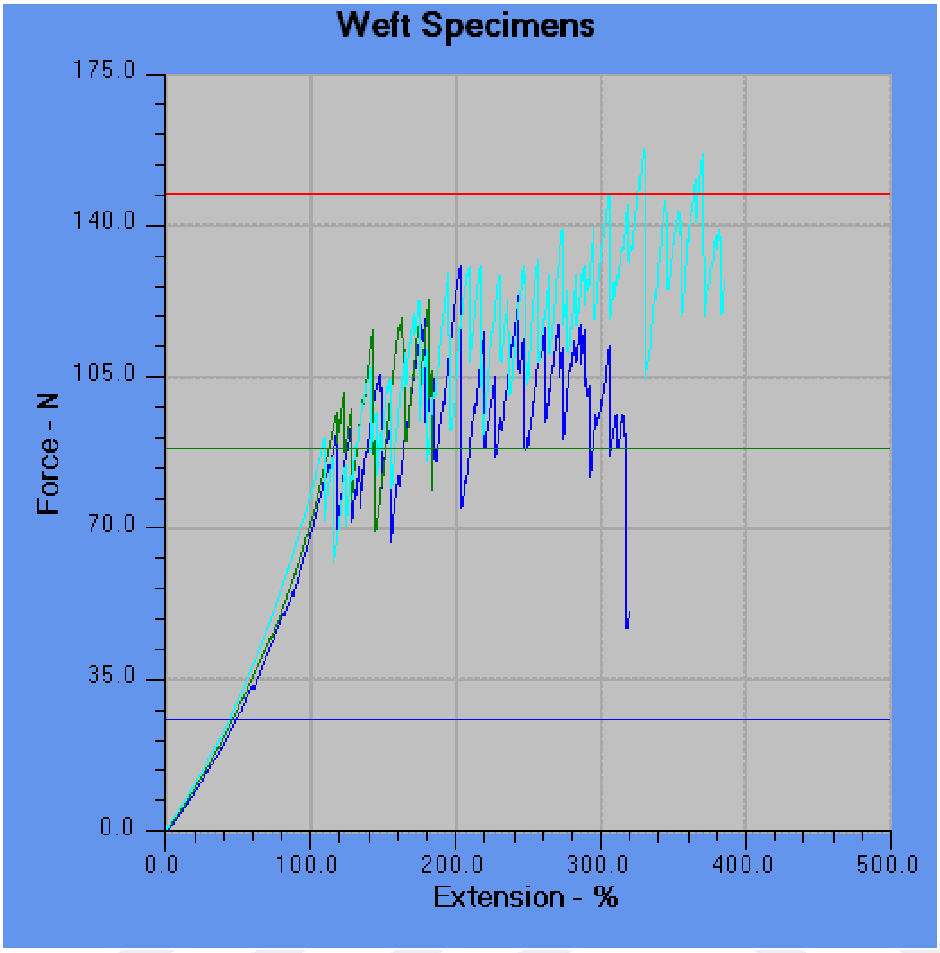

Figure 3.14 : Tear strengths of weft specimens.

As a result of the experiment, it was observed that Silitex coated fabric had high tear strength in both directions.

3.1.2. Chemical test results

3.1.2.1. Perspiration fastness test and results

The test is used to determine the resistance of the color of textile materials of all types and structures to the effect of human sweat.

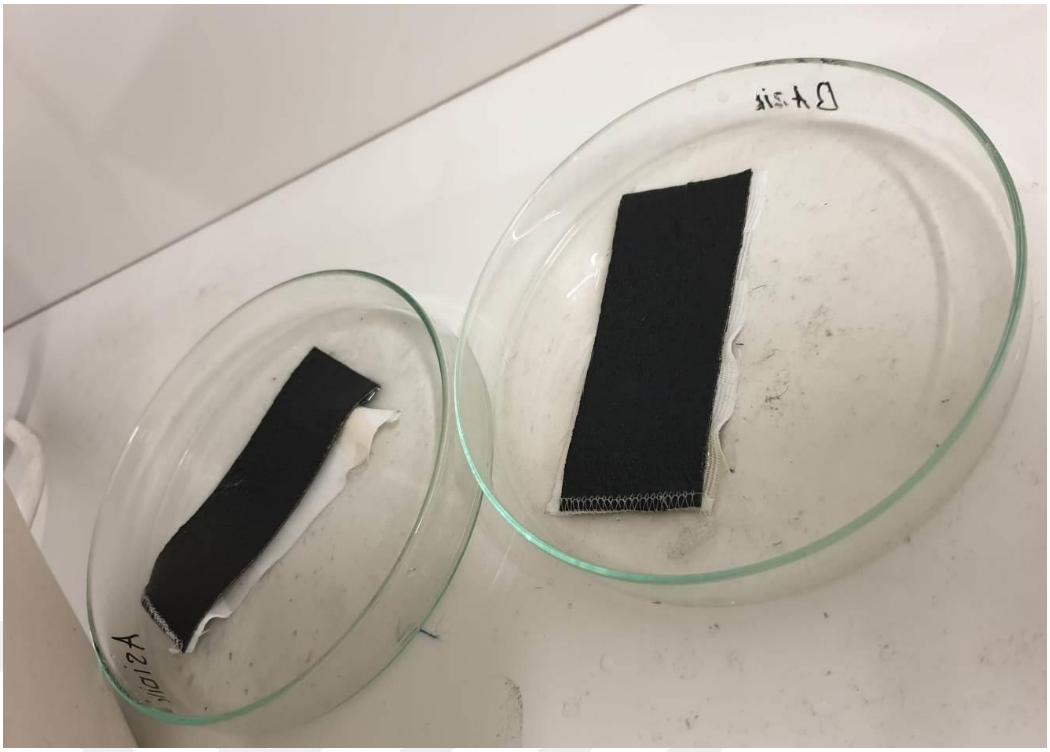

Figure 3.15: Acidic and basic solutions for perspiration fastness test.

Test Standard: Color Fastness Tests of Textile - Determination of color fastness to perspiration was measured according to TS 398 EN ISO 105-E04 standard.

In the experiment, the test device, oven, alkaline solution, acid solution, adjacent fabrics (multifibre) and gray scale were used. As a result of the experiment, the perspiration fastness values of the fabric were found to be 4-5 for acidic and basic solutions.

3.1.2.2. Rubbing fastness test and results

The resistance of the product against the color contamination of other materials as a result of rubbing was measured.

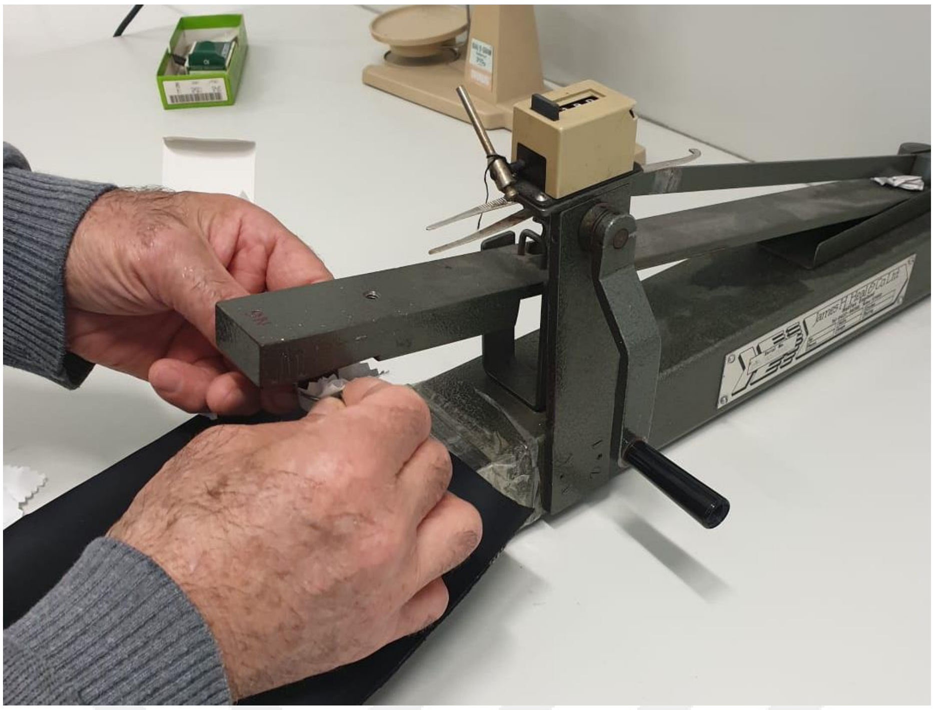

Figure 3.16: Rubbing fastness test device.

Test Standard: Color Fastness Tests of Textile - Determination of color fastness to rubbing was measured according to TS 717 EN ISO 105-X12 standard.

The test device, cotton rub fabric, soft back waterproof sandpaper and gray scale were used for the experiment. Measurements were made for both wet and dry rubbing. The test result for dry rubbing was 3, whereas the result for wet rubbing was 4.

3.1.3. Comfort test results

3.1.3.1. Water vapor permeability test and results

Water Vapor Permeability test measures the amount of water vapor that passes through a fabric. Average value of weights of fabric samples (with Silitex and without Silitex) were calculated at each stage.

Test Standard: BS 7209:1990 standard was applied to fabric and ERGE Water Vapor Permeability test device was used for the test.

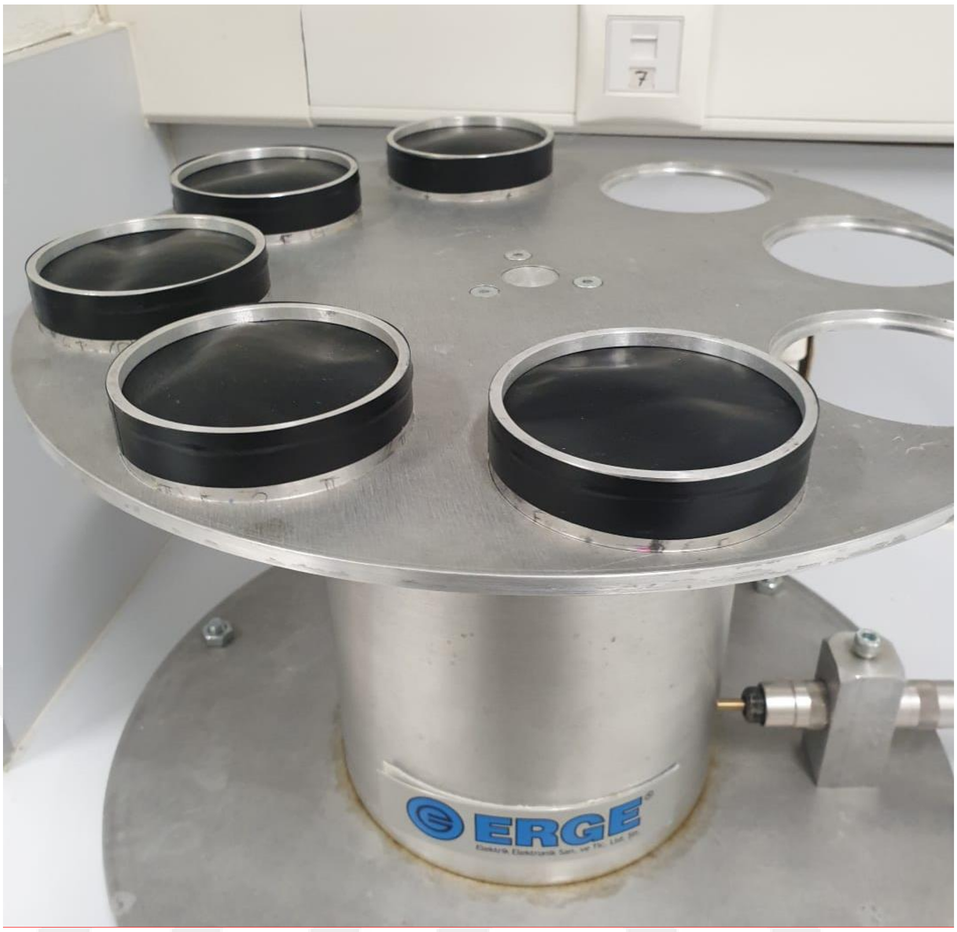

Figure 3.17: Rotating water vapor permeability test device.

Table 3.7: Water vapor permeability of fabric without Silitex test results.

Test Samples	Initial weight (g)	Final weight (g)	Water vapor transmission of fabric without Silitex and adhesive material (l/m^2/s)
T1	148,386	147,264	1015,41
T2	146,761	145,703	957,49
T3	145,034	144,009	927,625
T4	147,217	146,244	880,565
T5	148,973	147,955	921,29
Mean Value	147,2742	146,235	940,476

The whole test procedure was done again for the Silitex integrated fabric. After the process was completed, Silitex integrated test samples were weighed and calculations were done in the same way.

Table 3.8: Water vapor permeability of fabric with Silitex test results.

Test Samples	Initial weight (g)	Final weight (g)	Water vapor transmission of fabric with Silitex and adhesive material (l/m^2/s)
T1	147,246	147,174	65,16
T2	145,582	145,517	58,825
T3	135,022	134,95	65,16
T4	158,772	158,698	66,97
T5	151,18	151,104	68,78
Mean Value	147,5604	147,4886	64,979

Table 3.9: Water vapor permeability of fabric test results.

Test Samples	Water vapor permeability of fabric without Silitex and adhesive material (l/m^2/s)	Water vapor permeability of fabric with Silitex and adhesive material (l/m^2/s)
T1	1015,41	65,16
T2	957,49	58,825
T3	927,625	65,16
T4	880,565	66,97
T5	921,29	68,78
Mean Value	940,476	64,979

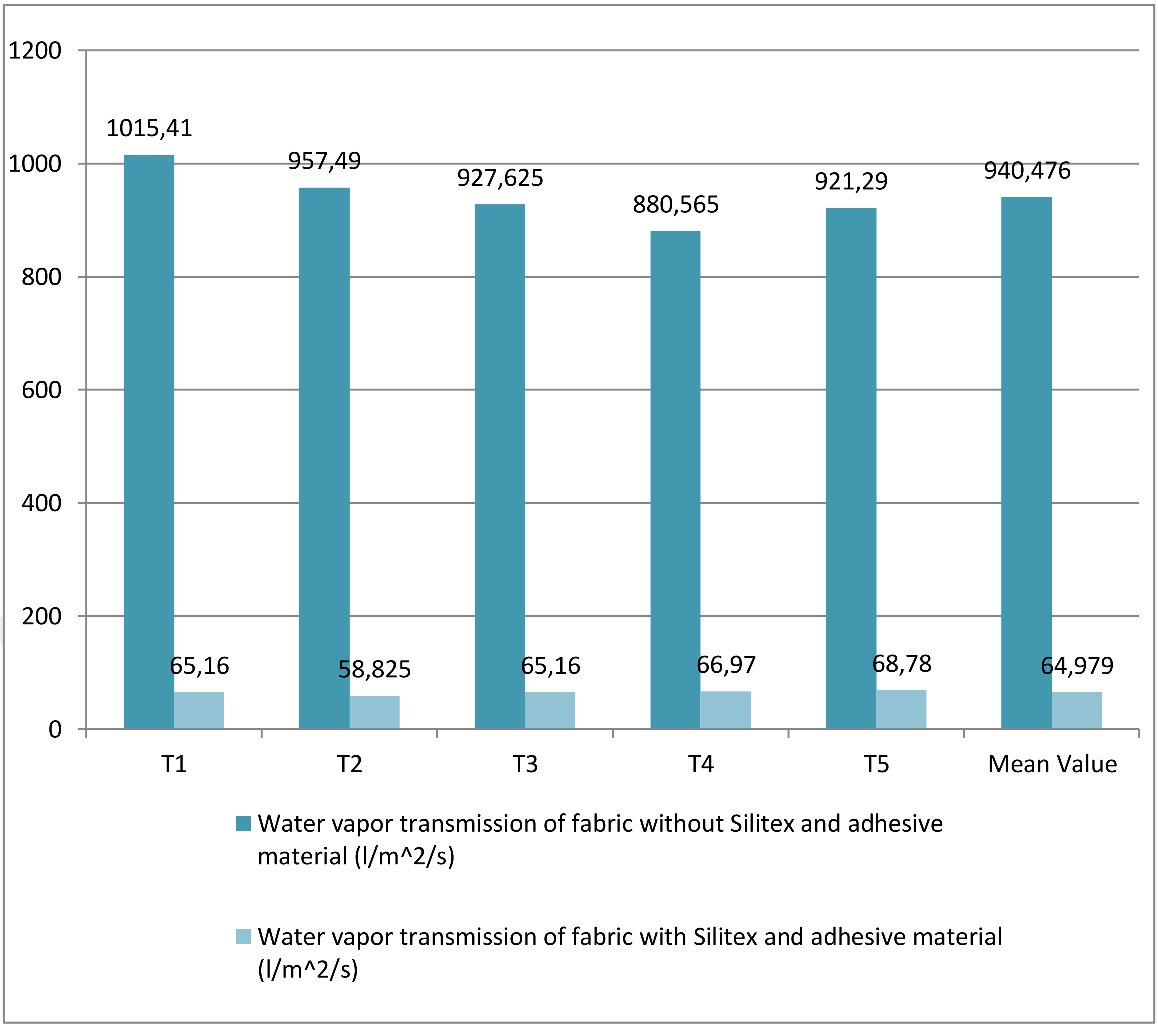

Figure 3.18 : Comparison of water vapor permeability test results.

3.1.3.2. Air permeability test and results

Air permeability properties of knitted and Silitex integrated fabric were measured by PROWHITE AIR PERMEABILITY TESTER.

Test Standard: TS 391 EN ISO 9237 standard were used to fabric.

Figure 3.19: Air permeability test device.

Table 3.10: Air permeability of fabric without Silitex test results.

Test Samples	Air permeability of fabric without Silitex and adhesive material (l/m^2/s)	Air permeability of fabric with Silitex and adhesive material (l/m^2/s)
T1	574	0
T2	560	0
T3	571	0
T4	566	0
T5	528	0
Mean Value:	559,8	0

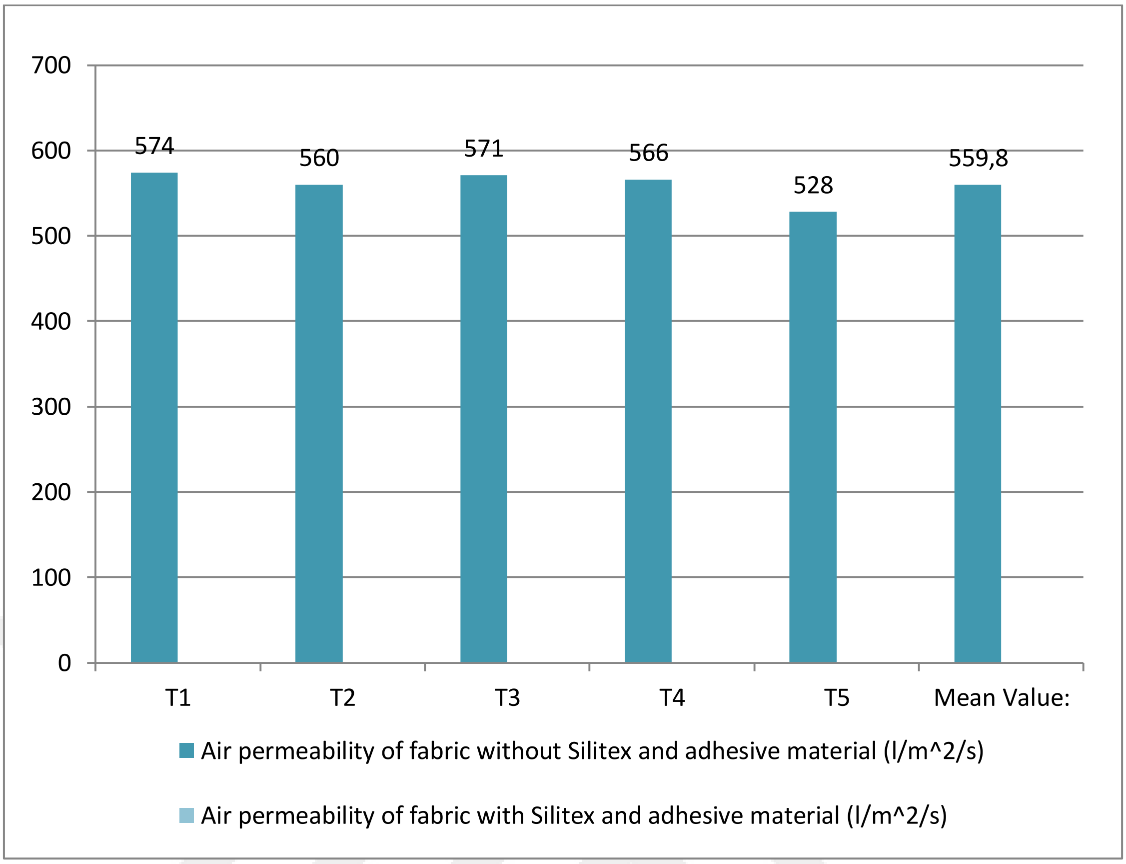

Figure 3.20 : Comparison of air permeability test results.

The air permeability of the fabric could not be measured after Silitex and adhesive material were integrated onto fabric. No results were received because the air was not passed through Silitex.

3.1.4. Electrical test results

The resistivity and shielding tests were conducted according to the ASTM D257 standard: Standard Test Methods for DC Resistance or Conductance of Insulating Materials.

As seen in Table 3.11 and Graph 3.9, the shielding effectiveness was the highest for the Silitex coated with adhesive material treated with heat. The shielding effectiveness observed for the Silitex coated without adhesive material untreated with heat was higher than that observed for only Silitex material up to around 600 MHz. After 600 MHz, the shielding effectiveness values observed for both of these materials were similar. These results indicate that the heating process had an obvious impact on the shielding of the material.

Table 3.11: Shielding Effectiveness of Fabric.

	Shielding of Fabric (dB)		
Frequency (MHz)	Silitex coated without adhesive material (untreated with heat)	Silitex coated with adhesive material (treated with heat)	Only Silitex
105 MHz	34,68	41,21	30,54
195 MHz	33,88	40,64	31,93
300 MHz	32,92	40,01	32,01
405 MHz	33,29	40,56	32,38
495 MHz	33,44	40,75	32,70
600 MHz	32,62	40,12	32,46
705 MHz	33,08	40,68	32,65
795 MHz	33,13	40,90	32,96
900 MHz	32,52	40,12	32,17
1005 MHz	32,73	40,66	32,43

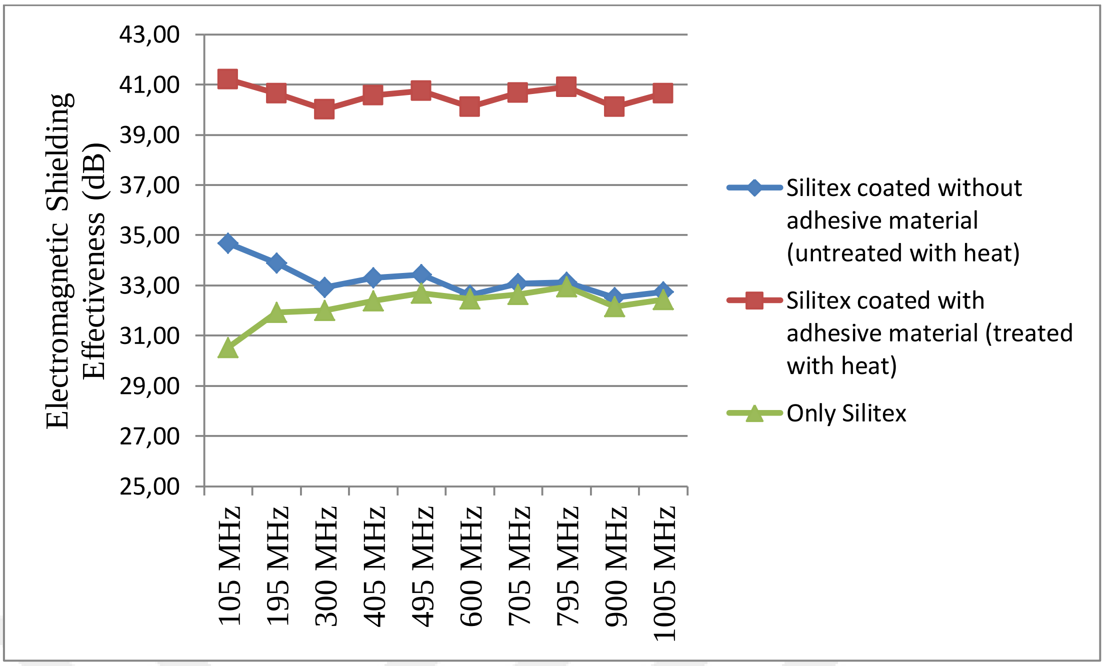

Figure 3.21 : Electromagnetic Shielding Effectiveness (dB).

The surface resistivity of the materials: silver side of the Silitex, silicone side of the Silitex, polyester fabric, and silicone side of the polyester fabric coated with Silitex. The voltage and the current used in the test were taken as 0.02 V and 20 mA, respectively. The resistivity was the lowest in the case of silver side of Silitex since it is the most conductive among these materials. The resistivity of the polyester fabric was the highest as expected.

Table 3.12 : Surface Resistivity of Fabric.

Material	Surface Resistivity (ohm)
Silver side of the Silitex	186
Silicone side of the Silitex	4070
Polyester fabric	12380
Silicone side of the polyester fabric coated with Silitex	400

3.1.5. Surface electromyography (sEMG) experiments and results

Every muscle contains muscle fibers which are controlled by motor neurons. These neurons transmit bioelectrical signals from the central nervous system to relevant muscle. Muscles create bioelectrical signals when they are strained. EMG is a device which measures the bioelectrical activity of muscles that are in motion. Electromyography records the voltages of bioelectrical waves of muscles, and then convert them to numerical values. The stronger the contraction of muscle, the higher the value of electrical activity displayed on the screen is. In this study, the signals are collected by the eMotion sEMG (surface EMG) with 4 sensors (16g / sensor). Each of these sensors has 3 electrodes which are called anode (+), cathode (-) and ground. The sensors are put on subject skin, the anode and cathode are placed on muscle and the ground is placed a little farther away from them.

The experimental protocol employed in this pilot study was retrieval of EMG signals from human subjects during a standardized two different conditions: while wearing a NMES with Silitex tapes and in motion, while wearing a NMES with Silitex tapes and in motionless position. The collected EMG signals were synchronized with a metronome at 100 bpm (beats per minute). 5 volunteer human subjects took two positions with each beat of the metronome for total 20 seconds.

A wireless EMG equipment with four channels was used for data collection. Each channel was connected to soleus muscle on the human body. Three electrodes (positive, negative and ground) were placed on each muscles group using the straps that came with the EMG equipment. Before placing electrodes, each subject’s skin was cleaned as directed in EMG equipment manual.

The measurements were taken based on the Soleus muscles of five subjects. The RMS values of these measurements were computed with the EMG analysis program, MegaWin. Mean values of the measurements computed for each subject were calculated.

Table 3.13: Paired Two Samples for Means.

t-Test: Paired Two Sample for Means	Standing motionless (Only device stimulation)	Jumping Jack movement (muscle contraction+device stimulation)
Average	1770,466667	1754,566667
Variation	4379,311111	32349,52222
Observations	5	5
Pearson Correlation	0,289436129	
Hypothesized Mean Difference	0	
df	4	
t Stat	0,205821741	
P(T<=t) one-tail	0,42349054	
t Critical one-tail	2,131846786	
P(T<=t) two-tail	0,84698108	
t Critical two-tail	2,776445105	

3.2. User Survey Results

The 20 volunteers participated experiments. The volunteers shared their feelings by the help of the survey after the experiments. The aim of survey was benchmarking perceptions of volunteers. Their features such as their age, weight and height were asked to subjects and also survey contained different questions about physiological-psychological effects of designed NMES device on the human subjects and effect of aesthetic appearance. The volunteers' survey reults is given below:

Table 3.14 : User survey demographic results.

	Age (year)	Weight (kg)	Height (cm)
Volunteer 1	39	69	162
Volunteer 2	47	58	167
Volunteer 3	23	57	168
Volunteer 4	26	59	159
Volunteer 5	23	57	168
Volunteer 6	36	52	160
Volunteer 7	27	70	178
Volunteer 8	27	50	165
Volunteer 9	31	56	168
Volunteer 10	26	48	164
Volunteer 11	58	80	175
Volunteer 12	27	76	193
Volunteer 13	33	80	178
Volunteer 14	25	75	180
Volunteer 15	30	83	185
Volunteer 16	33	73	179
Volunteer 17	31	70	181
Volunteer 18	29	55	163
Volunteer 19	55	85	183
Volunteer 20	36	72	178
Mean	39	69	162

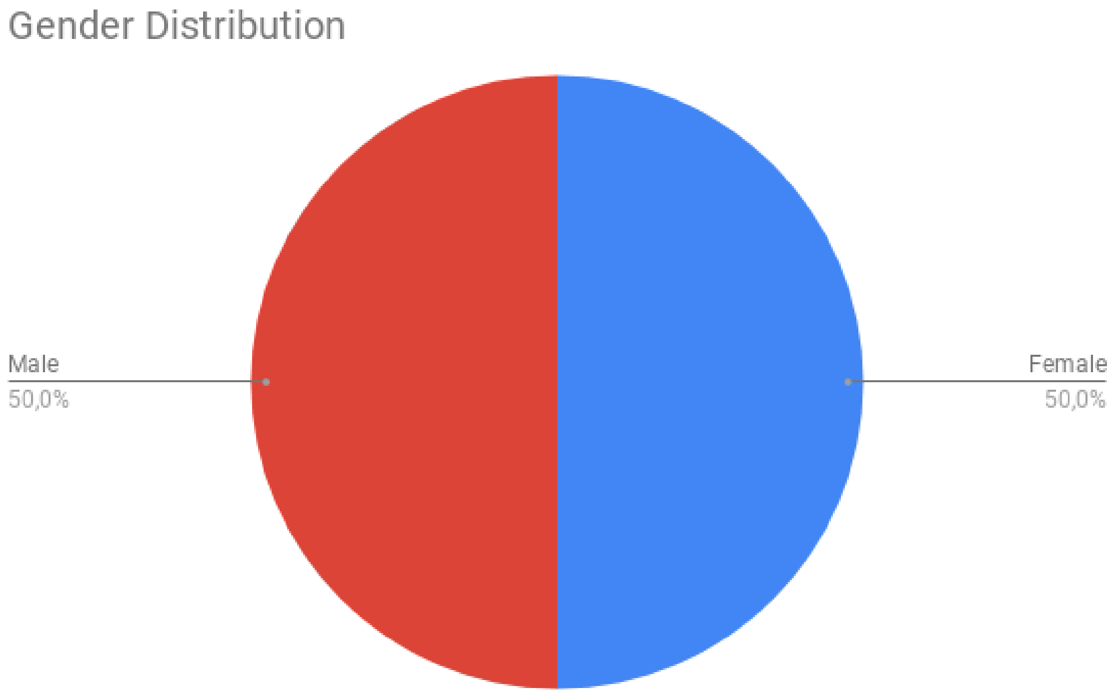

Figure 3.22 : Gender distribution.

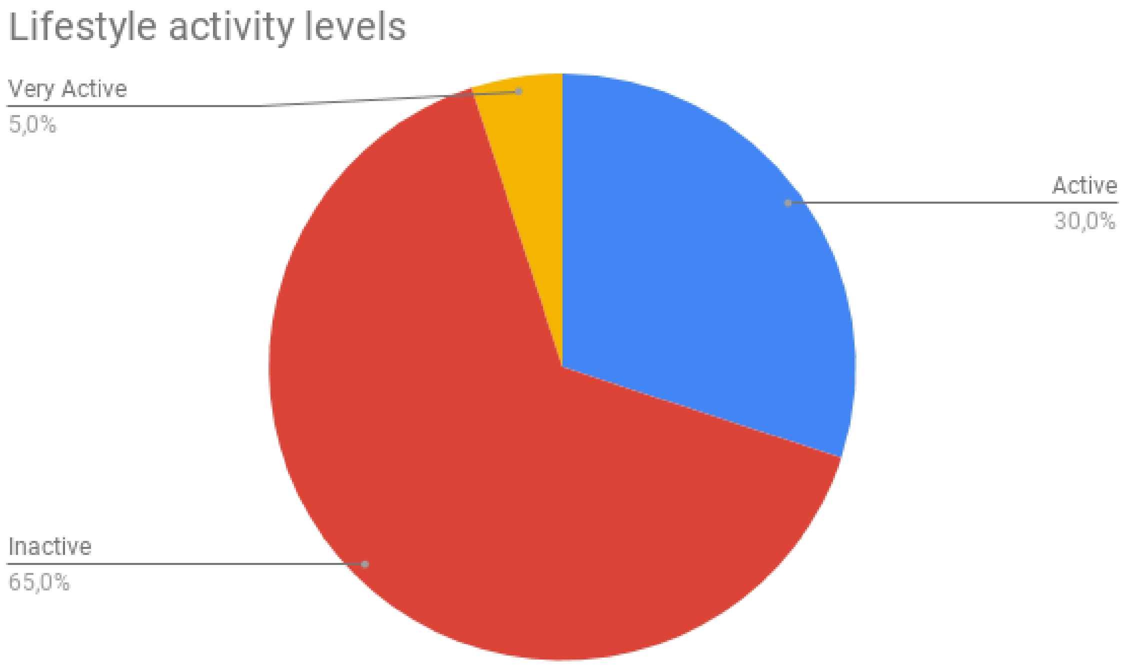

Figure 3.23 : Lifestyle activity levels of users.

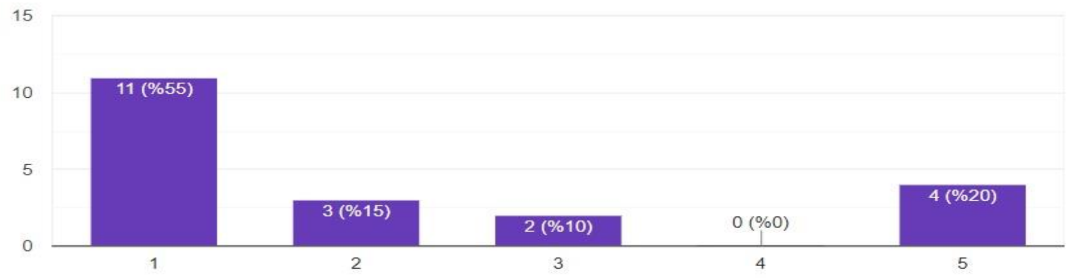

Figure 3.24 : Product Satisfaction (1 very satisfied, 5 less satisfied).

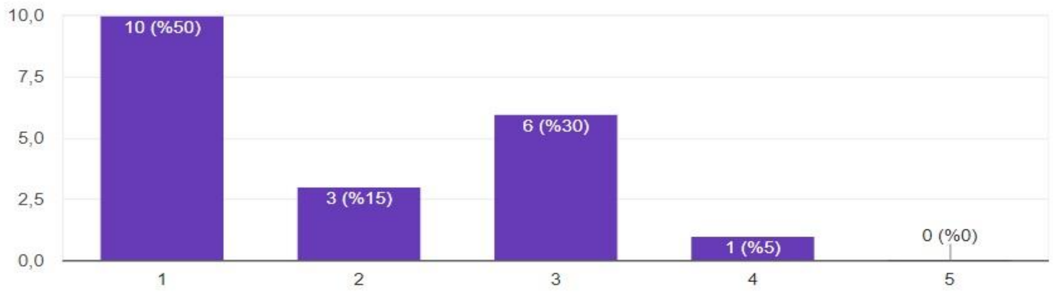

Figure 3.25 : Pain during experiment (1 min, 5 max).

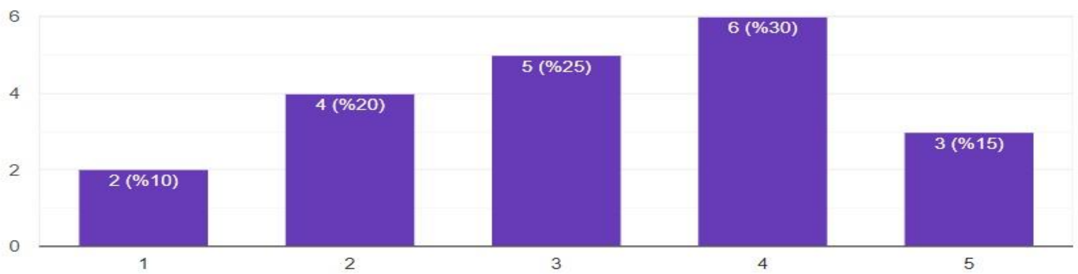

Figure 3.26 : Effect on their feeling of fatigue during using.

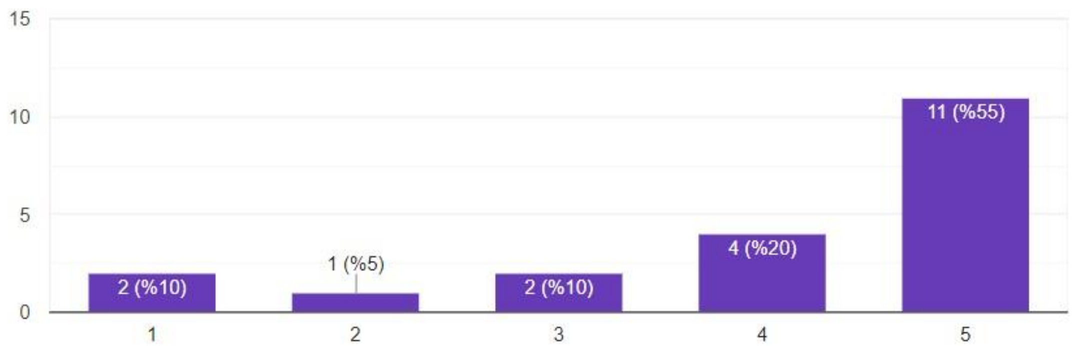

Figure 3.27 : Effect of aesthetic styling.

4. EVALUATION AND DISCUSSION

Several tests were applied to the fabric used for prototype design before and after integrating Silitex on its surface. Fabric elongation and tensile strength test was showed extensions of warp specimens were 197,40% and weft specimens were 148,45%. As a result, Silitex integrated fabric was found to have good elongation and recovery performance for weft and warp samples. It was determined that warp samples had higher elongation and tensile strength than weft samples.

Integrating Silitex on fabric surface basis weight is increased from 2,817 g/dm² to 6,876 g/dm² and has percentage of change affected some parameters such as comfort performances. As an example, air permeability test results for fabric without Silitex is 559,8 l/m²/s while for Silitex integrated fabric is 0 l/m²/s. Besides, water vapor permeability test results for fabric without Silitex is 940,476 l/m²/s while for Silitex integrated fabric is 64,979 l/m²/s and percentage change is approximately 93.1%. Bursting strength of fabric was measured as 18.22 kPa; however, after Silitex coating on fabric surface, the knitted fabric acted like woven fabric and any results were taken.

The paired sample t-test for means was performed on these EMG experiment results. This test was conducted between EMG values taken when the subjects were performing the jumping jack movement (muscle contraction+device stimulation) and when they were standing motionless (only device stimulation). The null hypothesis for this test was that there was no significant difference between the mean values of subject response when doing jumping jack and standing motionless. According to the test results (Table 3.13), the t critical two-tail value (2.78) and p value (0.85) were higher than the t stat value (0.20) and the alpha value (0.05), respectively, indicating that the null hypothesis could be accepted. Hence, there is no significant difference between the subject responses and the device stimulation is enough to contradict the muscles even without doing the jumping jack movement.

The survey taken by 10 female and 10 male subjects mean age of which was 39 and average height and weight of which were 162 and 69 respectively. The majority liked the aesthetic appearance of the device. Most of volunteers did not feel pain when use the device, and product satisfaction is very high.

Considerig all results and interpretations, it was determined that NMES device can give good results in muscle strengthening and injuries treatment.

5. SUGGESTIONS

The size adjustment was difficult when the device was fixed to the skin. It was always difficult to maintain the same tightness when placing the device. Therefore, different responses were obtained in each body. So, the design should be further developed. A design can be considered where the booster can be integrated into the fabric. Because the user applications are made in different environments, the neural effects may be different according to the environmental characteristics. An immeasurable effect, but every user should try the product in the same test environment. Bioelectrical measurements of the multiple muscle groups should be performed. Thus, more meaningful results can be obtained. By the help of surface EMG device, electrical changes in muscles can be calculated and analyzed. It was also a challenge for the booster to work with the battery. To ensure ease of use, the booster should be designed as rechargeable.

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