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CHOSUN UNIVERSITY

August 2018
Doctor's Degree Thesis

A study on textile-type resonant coils for wireless power transmission in human activity-based energy harvesting

Graduate School of Chosun University
Department of IT Fusion Technology
Min Joo Jeong

조선대학교
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A study on textile-type resonant coils for wireless power transmission in human activity-based energy harvesting

인체 활동기반 에너지 하베스팅 소자에서의
무선전력전송을 위한 섬유형 공진코일 연구

August 24, 2018

Graduate School of Chosun University
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A study on textile-type resonant coils for wireless power transmission in human activity-based energy harvesting

Advisor : Prof. Youn Tae Kim

This thesis is submitted to The Graduate School of Chosun University in partial fulfillment of the requirements for the Doctor's degree

April 2018

Graduate School of Chosun University
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This is to certify that the Doctor's Thesis of Min Joo Jeong

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Table of Contents

Collection @ chosun

조선대학교
CHOSUN UNIVERSITY

Collection @ chosun

조선대학교
CHOSUN UNIVERSITY

List of Figures

Collection @ chosun

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Collection @ chosun

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Collection @ chosun

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List of Tables

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Acronyms

ICT	Information and Communication Technology
WPC	Wireless Power Consortium
A4WP	Alliance for Wireless Power
PMA	Power Matters Alliance
PA	Power Amplifier
IoT	Internet of Things
NFC	Near Field Communication
GPS	Global Positioning System
PCB	Printed Circuit Board
CST	Computer Simulation Technology
TENG	Triboelectric Generator
FSTENG	Fiber-based Single-electrode Triboelectric Nanogenerator
ETRI	Electronics and Telecommunications Research Institute

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SEM	Scanning Electron Microscope
T/m	Twists per Meter
ISM	Industrial, Scientific and Medical
AC	Alternating-Current
DC	Direct-Current
PU	Polyurethane
UHF	Ultra High Frequency
RF	Radio Frequency

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요 약

인체 활동기반 에너지 하베스팅 소자에서의 무선전력전송을 위한 섬유형 공진코일 연구

정민주
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조선대학교 대학원, IT 융합학과

이 논문은 의류에 통합 될 수 있는 전도성 원사로 만들어진 공진 코일과 자기 공진 커플링을 사용하는 무선 전력 전송 방법을 제시한다.
전도성 실은 은도금 된 구리 및 폴리에스테르 필라멘트로 구성되었다. 실과 구리로 구성되는 각 공진 코일의 전송 특성은 시뮬레이션 및 측정 도구를 사용하여 비교되었다. 전도성 실로 구성되는 공진 코일의 신호 손실은 구리선으로 구성되는 코일의 신호 손실보다 높았다. 그러나 전송 거리가 6.5 cm 미만일 때 신호 손실 변동의 증가는 1 dB 미만이었다.

도전사로 구성되는 공진 코일을 신발과 바짓단에 위치하고, 수신 된 교류 전력을 AC-DC 컨버터를 사용하여 직류 전력으로 변환 한 후에 전송 효율을 측정 하였다. 측정 결과는 최대 전송 효율이 50%임을 보여주었다. 평균적인 전달 효율은 45%였다. 또한, 피검자가 6 km/h의 속도로 움직일 때 40% 이상의 탁월한 전송 효율을 나타냈다.

또한 인체의 팔에 착용 된 공진 코일의 전송 특성은 시뮬레이션 및 측정 툴을 사용하여 측정되었다. 전도성 실은 폴리우레탄으로 코팅 된 구리와 폴리에스테르 필라멘트로 구성되었다. 전도성 실로 구성된 공진 코일의 공진 주파수 변화는 코일 길이, 스티치 간격, 직물 두께를 이용한 방정식으로 결정될 수 있다. 송수신 코일의 측정 공진 주파수는 코일이 착용되었을 때 13.56 MHz의 공진 주파수가 되도록 설계되었다. 공진 코일은 다양한 속도

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로 움직이는 착용자의 팔에 착용되었고, 전송 효율은 교류 직류 변환기를 사용하여 측정되었다. 측정 결과는 피험자가 6km/h 속도로 움직일 때 공진 코일이 다리가 아닌 팔 주위에 착용되었지만 최대 전송 효율이 55.1% 였고 평균 전송 효율은 52.1%였다.

향후 섬유형 코일은 차세대 웨어러블 디바이스의 착용감과 지속적인 전력 공급을 극복하는 통합 솔루션이 될 것으로 기대된다.

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I. Introduction

A. Wireless charger market

Led by mobile phones, small appliances and wearables, shipments of consumer electronics devices enabled with wireless charging rose 40 percent in 2017, compared to the previous year. In all, nearly 500 million devices with wireless charging shipped last year as shown in Figure 1.1, according to IHS Markit, a world leader in critical information, analytics and solutions [1].

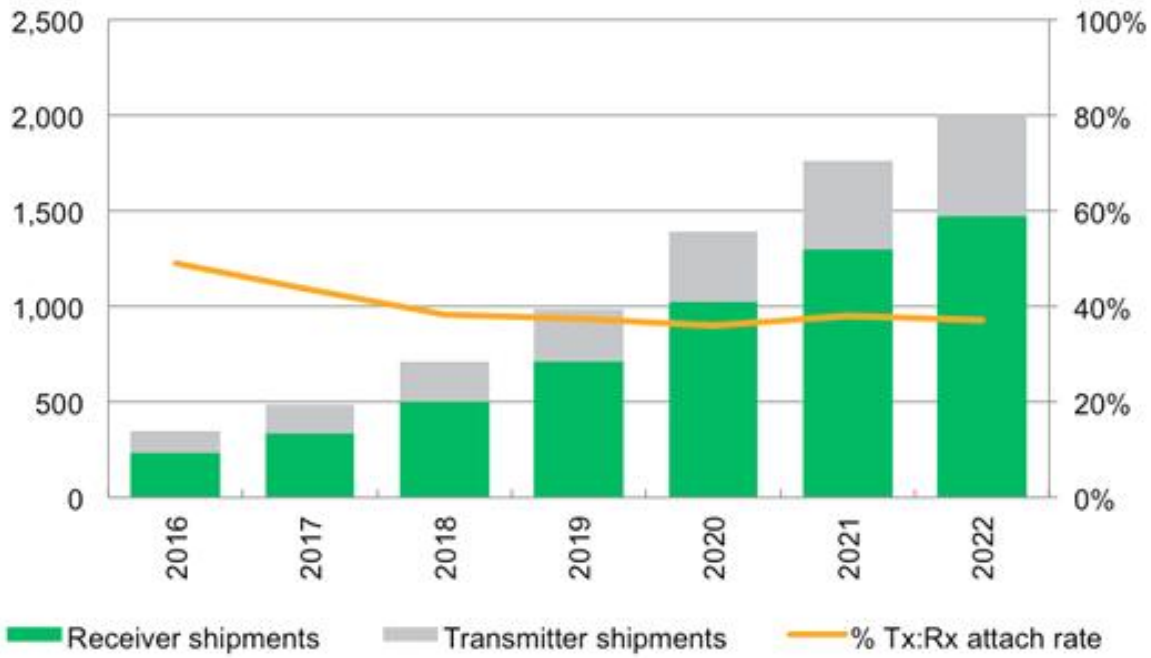

Figure 1.1 World market for wireless power and charging(millions of units).

Mobile phones were primarily responsible for the strong growth in wireless power technology in 2017, after Samsung set a precedent with its flagship Galaxy S8 smartphone in April 2017. Apple followed in November 2017, adding the technology to its new iPhone devices, including the iPhone 8 and 8 Plus. The Apple Watch, which has featured a proprietary, low frequency

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charging solution since its launch in 2015, led wireless charging in the wearable devices category in 2017. Smart watch devices launched by smartphone manufacturers are expected to continue to drive growth in the wearable segment, which is expected to exceed 90 million units shipped in 2022. According to the latest Wireless Power Market Tracker from IHS Markit, consumer awareness of wireless charging technology exceeded 80 percent in all regions (United Kingdom, United States, China, South Korea). However, the number of respondents reporting actually used wireless charging technology was still relatively low, averaging only 29 percent across all regions in 2017. In the past, the presence of several competing wireless charging standards was a barrier to adoption.

Consumers charge their mobile devices more than 70% at least once per day as shown in Figure 1.2. This will increase as transitions to smart phones increase.

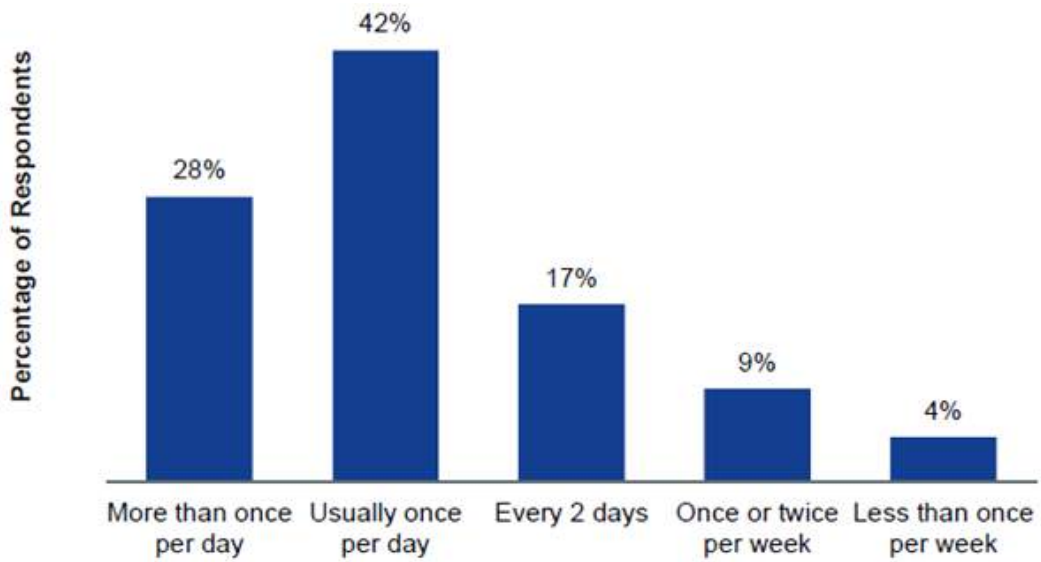

Figure 1.2 Breakdown by how often consumers charge their mobile phone.

Home, at the office and in the car are the most common places for people to charge as shown in Table 1.1. Power demands will continue to increase with 4G, 5G rollout and trends towards larger, higher definition displays, etc.

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Table 1.1 Rank of the most common places to charge.

Rank the most common places to charge	Number of Respondents		
	1st	2nd	3rd
At home	85%	10%	1%
At work (at my desk)	11%	54%	17%
In the Car	1%	26%	46%
On public transport (e.g. train, plane)	1%	3%	9%
In a public place (e.g. coffee shop)	1%	4%	24%
Other - Please Specify	1%	2%	2%

B. Wireless charging technology

Table 1.2 Wireless charging standards.

MOST COMMON WIRELESS CHARGING STANDARDS			
Standard organization	Wireless Power Consortium (Qi)	AirFuel Alliance	AirFuel Alliance (Rezence)
Method	Inductive	Inductive	Resonant
Frequency range	80 to 300 kHz	200 to 300 kHz	6.78 MHz
Max. power Xfr range	15 W to 2 kW	5 W	70 W
Max. Xfr range	5 mm	5 mm	50 mm
No. charging devices	One	One	Multiple ok.
Communications system	Load modulation	Load modulation	Bluetooth

Table 1.2 shows the standards for wireless charging technology. Wireless Charging has had a hit-or-miss relationship with the mobile industry, dipping in and out of product ranges and flitting between spec sheet features and accessory status [2]. However, the second half of 2017 and early 2018 has seen a major shift in the industry's balance of power, led by Apple's decision to pick a side. There are currently only two major groups producing wireless charging technologies for mobile products, the Wireless Power Consortium and the AirFuel Alliance (formerly A4WP(Alliance for Wireless Power) and

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PMA(Power Matters Alliance)). However there's clearly a single dominant player when it comes to market share, and that's the WPC's Qi standard, which accounts for approximately 90 percent of all wireless charging products.

After a long period of industry indecision between the WPC and AirFuel standards, 2017 saw Apple adopt Qi technology for its iPhone 8 and iPhone X, adding major clout to the standard that in essence forced the industry to finally pick a group. Although Samsung, a larger smartphone manufacturer by global volume, adopted wireless charging long before Apple, it's latest products hedge their bets with support for both Qi and PMA.

Come 2018, Apple's decision proved to have trickle-down effects for the wireless charging industry. Powermat joined the WPC, specifically citing Apple's use of the Qi standard as a determining factor. Powermat is now contributing its technology to the WPC, and the partnership will likely end up producing chargers with both Qi and PMA standards like its newest Charging Spot 4.0.

Even before Apple's adoption and the Powermat partnership, the Wireless Power Consortium's inductive Qi standard had a prominent industry profile, as it powers a range of smartphones, accessories and products. The PMA standard, which is now folded into AirFuel, has also appeared in a number of smartphones and also struck deals to provide charging stations to businesses such as Starbucks. Both of these standards are based on inductive charging technology, which is typically quite short range and can be quite finicky. Rezense, the old A4WP standard was based on resonance technology, but this design has yet to appear in any smartphones.

Inductive and resonance-based technologies produce quite different results from an end user's perspective, despite being based on the same engineering principle that coils of wire can be used to transmit power over the air.

The only real differences between Qi and PMA are the transmission frequencies and connection protocols used to communicate with devices and control power management. Resonant charging is a little different, typically

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operating over a larger distance of a couple of inches by tuning the frequency of the oscillation to precisely match between the receiver and transmitter. This allows for a longer transfer distance before power diminishes but with less optimal power transfer than induction technology. One of the other big benefits of a resonance design is that power can be transferred to devices regardless of their orientation in the magnetic field and can also power multiple devices from a single transmitter coil.

Qi also now has a resonance design in its 1.2 specification for longer power transfer up to 2.8 cm, but due to ensuring compatibility with existing Qi transmission frequencies, Q factor and heat limitations, it is not as effective at transmitting power over long distances as a system designed specifically for that purpose.

Although Qi may have the advantages associated with early adoption, AirFuel is now attempting to push both inductive and resonant technologies into single products. This would provide the best of both worlds and has added an interesting dynamic for device manufacturers to consider.

Even before Apple's adoption and the Powermat partnership, the Wireless Power Consortium's inductive Qi standard had a prominent industry profile, as it powers a range of smartphones, accessories and products. The PMA standard, which is now folded into AirFuel, has also appeared in a number of smartphones and also struck deals to provide charging stations to businesses such as Starbucks as shown in Figure 1.3 [3].

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Figure 1.3 Wireless phone charger in Starbucks.

Selected stores in Central London are offering Powermat wireless charging in the form of Powermat Spots, designated areas on tables and counters. The roll out will be begin in locations throughout the San Francisco Bay Area. From there, Starbucks and Duracell Powermat will push to install more than 100,000 built-in table charges in each of the approximately 7,500 Starbucks owned stores in the United States. The Duracell Powermat requires a special AccessCase or Ring to connect a phone with a wireless charging. The AccessCase runs about $30, while the special Ring will be available at select locations. When plugged into phone and placed on a Powermat Spot, the Powermat Ring wirelessly recharges battery.

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C. How the technology works

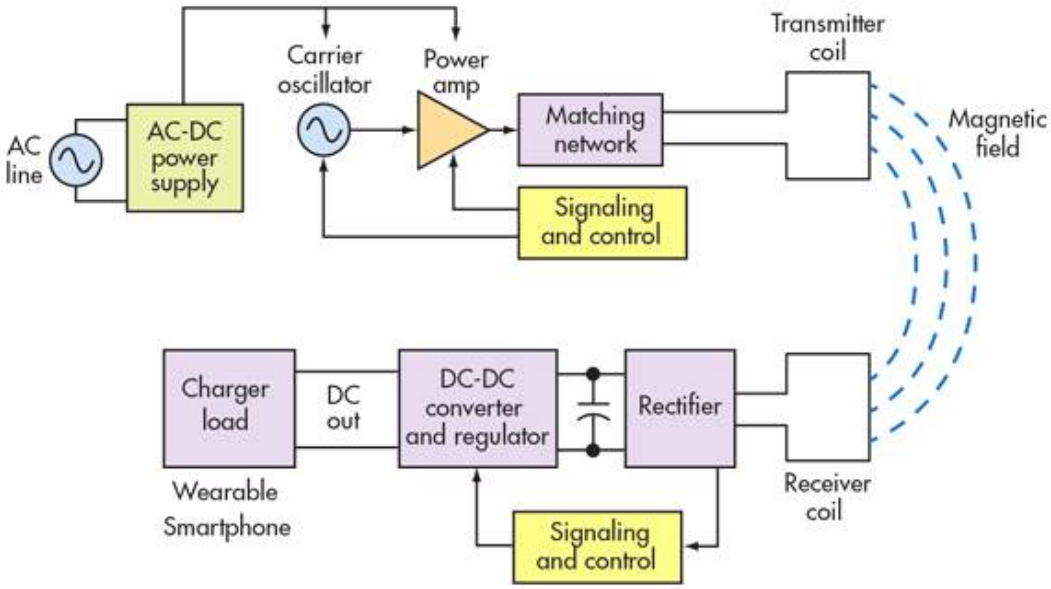

Figure 1.4 Wireless charging concept.

Wireless charging is based on the basic electrical principle of electromagnetic induction as shown in Figure 1.4 [4]. An AC power source is connected to a coil that generates a magnetic field; the field then induces an AC voltage in another coil in the device to be charged. The coils aren't electrically connected, but are physically close to one another so that sufficient magnetic field is present to induce a voltage and provide enough power to charge a battery.

The two coils form a transformer without a common core. The power source or transmitter coil is the primary winding and the receiving coil is the secondary winding. The coils are typically flat spirals of wire with no core.

The transmitter unit takes the AC power-line input that operates a DC power supply, which in turn powers an oscillator signal source at the desired frequency. This signal is called the carrier. Typical frequency range is 100 kHz to 10 MHz.

A power amplifier (PA) boosts the signal level to supply adequate power to

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the receiver. A matching circuit ensures maximum power transfer from the PA to the primary coil. The transmitter coil is usually embedded in a flat mat or pad upon which sits the device to be charged.

To transfer maximum power, the receiver coil must be perfectly aligned with the transmitter coil. This provides a coefficient of coupling near one. If the coils are misaligned, the coefficient of coupling will be significantly less, thereby decreasing the overall efficiency of power transfer. This physical limitation is one of the main disadvantages of wireless charging.

The AC from the receiver coil is then rectified into DC and applied to a DC-DC converter/regulator that generates the DC output voltage, which goes to the battery charger in the powered device.

A unique feature running through today's wireless-charging standards is a communications facility between the transmitter and receiver. This communications path allows the transmitter and receiver to detect and identify one another and make internal settings appropriate to the device to be charged. One type of communication path uses coded signals that load-modulate the AC carrier. Another type of communication path employs wireless technology like Bluetooth.

A variation of the inductive-charging method exploits the concept of resonance. A capacitor is connected to the transformer coils to resonate them to the carrier frequency. This produces a higher current in the coils to boost energy transfer. However, its main benefit is that resonant coils needn't be perfectly aligned for usable coupling. Multiple devices can also be charged this way. Most wireless-charging systems in use today are non-resonant types.

D. Inductive and resonance charging

There are some noteworthy distinctions between these two common methods of wireless charging as shown in Figure 1.5 [5].

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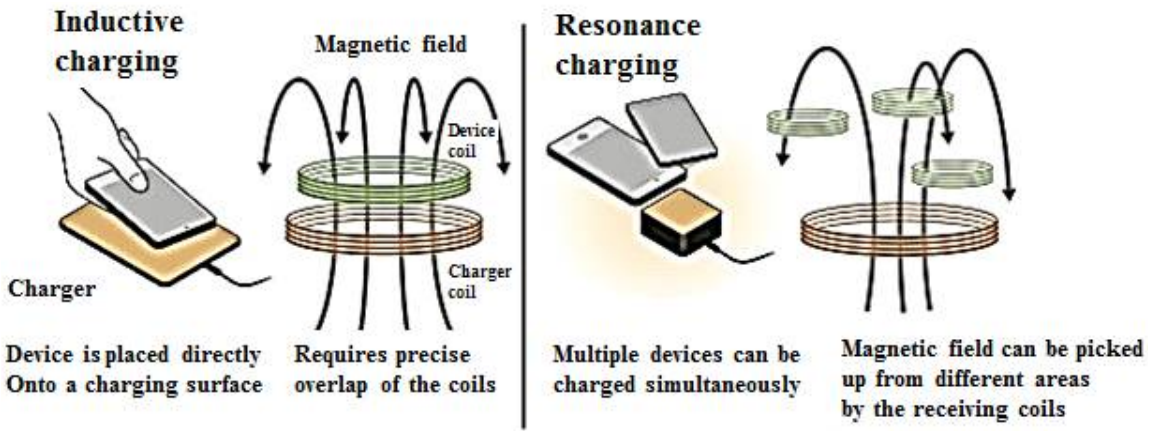

Figure 1.5 Inductive charging vs resonance charging.

Inductive technology, which is a closely coupled solution, is the type of compliance used by Qi. This technology transfers power using low-frequency resonant tanks (100-205 kHz) over very short distances (mostly anything under 10mm).

In 2009, the first standard for Qi had a 5W power requirement ("Low Power"). In 2015, that was increased to 15W capability ("Medium Power"). This year, Qi is hoping for over 100W ("High Power"). Those are currently in testing and should be rolled out later this year.

Inductive charging utilizes an electromagnetic field for transferring energy between two objects through electromagnetic induction. Energy is sent through an inductive coupling to an electrical device, which can use that energy to charge batteries or run the device.

The other wireless power technology, resonant, is considered a loosely coupled solution. Primarily championed by the AirFuel Alliance, this technology uses a high-frequency resonant tank (6.78 MHz) to transmit power over long distances (multitudes of feet). Resonant technology offers the ability to charge multiple devices at the same time, with a capability of up to 22W for upcoming systems.

Resonance charging involves two copper coils, with one attached to a power source as the sending unit, and the other attached to the device that's being charged (also referred to as the receiver). When objects of the same

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resonant frequency are placed close to each other, the energy produced is transferable between the pair.

E. Advantages and Disadvantages

The primary advantage of wireless charging is, of course, the elimination of a charging cable. This benefit also eliminates the generally unreliable connectors and wires associated with the cable. Other advantages are the ease and convenience of charging, and in smaller devices like a smart watch, the elimination of a connector saves space and lowers cost.

Several disadvantages crop up with wireless charging, too. First, there's the need for a charging pad with the transmitter and its coil, which is an extra cost item. Wireless is also more expensive because of the added coil and other components in the device to be charged. On top of that, the coil adds thickness to a smartphone or other device. Finally, wireless charging is much slower than direct cable charging due to the inherent inefficiency of the method. And don't forget that the device to be charged must be precisely aligned on the charging pad to ensure optimum coupling.

F. Wearable electronics

Wearable electronics can be worn on the body as implant or accessories. The designs often incorporate practical functions and features. Wearable devices can range from wrist wear, smartwatches, and fitness bands. To head wear; smart glasses and virtual reality googles, to smart bodywear. Smart wearables can be worn on the body and have the ability to connect to the internet, enabling data to be exchanged between a network and the device. Everyday objects that can be connected to the internet and be recognized by other devices and contribute information to a database are here to stay and are examples of the Internet of Things (IoT).

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Smart wearables can be worn on the body and have the ability to connect to the internet, enabling data to be exchanged between a network and the device.

Wearable electronics have actually been used for decades in common medical devices like hearing aids, pacemakers and others. Wearable electronics have evolved from life-saving devices to fashion accessories as shown in Figure 1.6 [6].

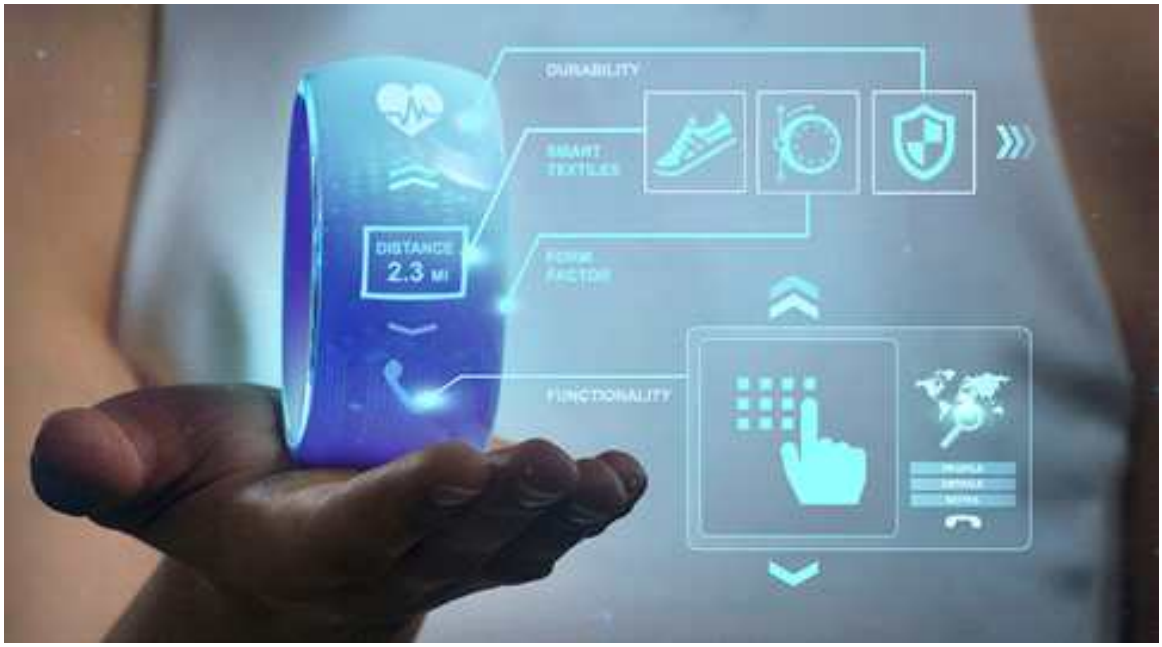

Figure 1.6 Wearable electronics.

Range from activity monitor bracelets, smart watches and smart glasses to GPS enabled shoes-all of which have growing market demand. Wearables are where the IoT becomes the "IoMe". Wearables must be powered by rechargeable batteries or other charging methods. Wireless power transmission is emerging as a key feature to be integrated in new wearable devices. The wearer can independently perform a variety of tasks without connecting to the wired charger.

Power transmission technology is currently being used to wirelessly charge

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portable devices [7]. In addition, an international standard has been developed for wireless body area networks that enables communication among various sensors that monitor human physical conditions [8]. However, the operating time and functions are limited by the battery life of the sensors and portable devices. These limitations can be overcome if the sensors and portable devices receive power to charge the battery through wireless power transmission [9]. So this thesis presents a wireless power transmission technology based on magnetic resonant coupling and uses textile-type resonant coils in human activity-based energy harvesting. Thus, they can be easily integrated into clothing, as shown in Figure 1.7. The signal losses of the textile-type resonant coils were measured and compared with simulation results. Further, the change in the transmission efficiency was measured when the subject wearing the coils was in motion.

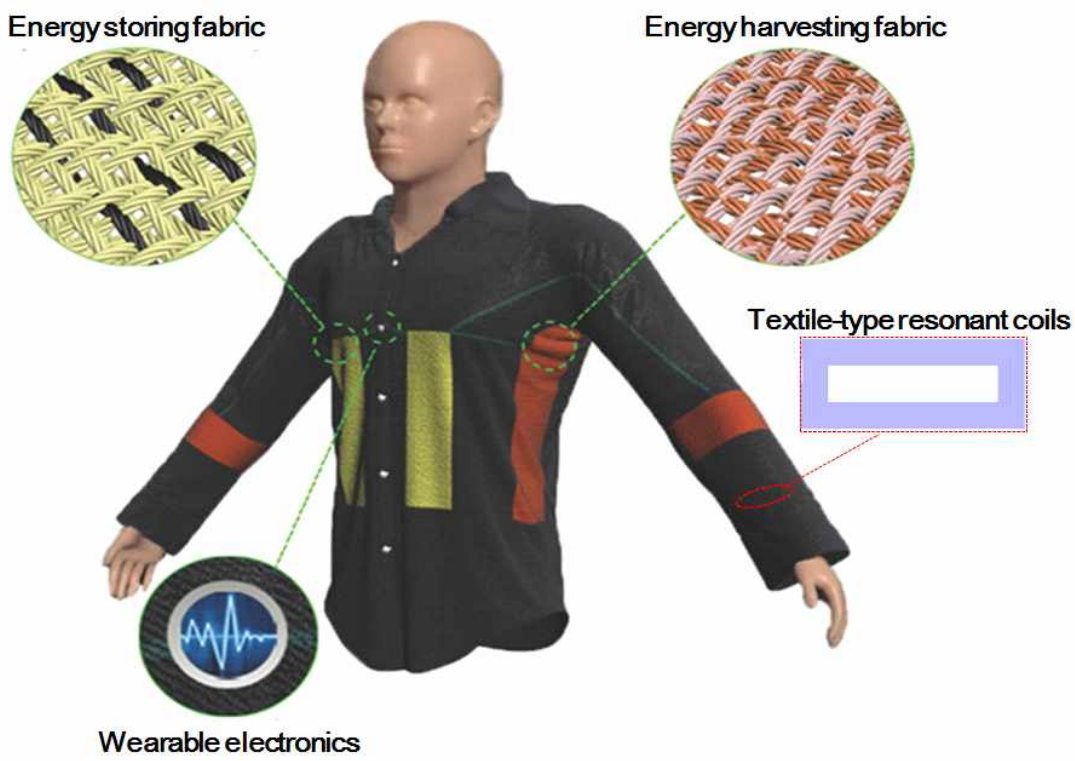

Figure 1.7 Textile technologies for wearable electronics.

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II. Previous methods

A. Smart clothing

Interest in smart apparel that combines apparel and information and communications technologies (ICT) has increased in the Internet (IoT) era, where everything is interconnected by the development of short range wireless communications (NFC), sensors and Bluetooth. Smart clothing is gradually getting closer to our skin due to the development of 'textile technology'. Also, it can be applied to various fields such as health, nursing care, and child care. Smart clothing is becoming more applicable to convenience, portability, and design in existing smart phones due to the development of textile technology and IT technology. It is expected that trends will be changed from wearable devices such as smart clothing to woven and garment-integrated devices in currently used accessories-type devices. Smart apparel, which has a form that is easily absorbed into everyday life, is expected to have a greater impact on the market than other smart devices. Even if a special measuring device such as a watch or a bracelet is not worn, a garment for measuring a variety of biometric information such as heart rate and momentum and expressing it through a smart device is being developed. Wearable technology is getting closer to our skin, and this is becoming reality with the development of fiber technology. As shown in Figure 2.1, the global designer Hussein Chalayan, who won the British Royal Medal of Honor and the British Designer of the Year Award, shocked the world by introducing a dress that could be manipulated with remote control in the 2000 Before Minus Now collection [10].

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Figure 2.1 Dress changing shape by remote control.

In the early stage of smart clothing development, if the development of conductive materials is mainly focused on embedding digital devices and functions in textile products, investing in product development for user's convenience such as portability and design has been concentrated recently. In the case of smart apparel to date, the main thing was to put clothes on the outside and put digital devices such as sensors on the outside, or put digital devices into clothes. It can be said that it is more like a wearable device with various electronic devices attached to clothes rather than smart clothes. These early smart apparel caused considerable inconvenience in daily life due to its weight and cumbersome appearance. Thus, it has been used only in a narrow range such as a hospital, a nursing home, and a fitness center. But now, with advances in textile technology and IT technology, there has been a way to alleviate many inconveniences. Convenience and portability have been added to the existing smart, and recently, the design has become applicable, and the smart clothing era is ready to start. Currently, accessory-type devices such as smart watches and smart bands are mainstream, but in the

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future, it is expected that the trend will be changed to a wearable device that integrates textiles and apparel such as smart clothing. Many companies around the world are spurring smart apparel development, and GOOGLE is one of them. As shown in Figure 2.2, GOOGLE launches PROJECT JACQUARD and launches full-scale smart clothing development [11]. Using conductive fibers, various objects such as shirts, car seats, sofas, chairs, and underwear are being studied so that they can act as touch panels such as the screen of a smart phone. Efforts are also under way to cooperate with Levis, which is famous for jeans, and to design technology.

Figure 2.2 Google project jacquard.

As shown in Figure 2.3, in Korea, Kolon Sports has launched a smart clothing called Life Tech Jacket [12]. The concept of respect for life was developed in order to ensure the safety of the victims in the distress. Technological features of the jacket include a tri-layered waterproof and windproof system and a wearable first-aid and survival kit. Other details

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include: oversized zip pulls for use with gloves, easy access shoulder and back straps for manhandling a companion in distress, and a wind turbine mounted onto the sleeve of the jacket can be angled to generate power throughout the day whilst the wearer is on the move, we can then charge devices such as GPS & smartphones for essential navigation and communication. A built-in Heatex system provides up to seven hours of heat up to a temperature of 40-50℃.

Figure 2.3 Life tech jacket by Kolong sport.

Smart fashion combining fashion and technology enables customers to wear technology while maintaining its functionality but not affecting beautifulness of clothing. Many researchers have developed communication technology for smart fashion; however, little research has been conducted to wireless power transmission for smart fashion. Wireless power transmission has emerged with the rapid development of information technology. Two representative wireless power transmission methods exist: inductive coupling and magnetic

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resonant coupling. The transmission efficiency of magnetic resonant coupling is higher than that of inductive coupling when the transmission distance is greater than two times the coil diameter. As shown in Figure 2.4, this power can be obtained using various energy harvesting technologies [13]-[15]; however, the harvested power should be transmitted wirelessly, such as through sleeves and trouser cuffs.

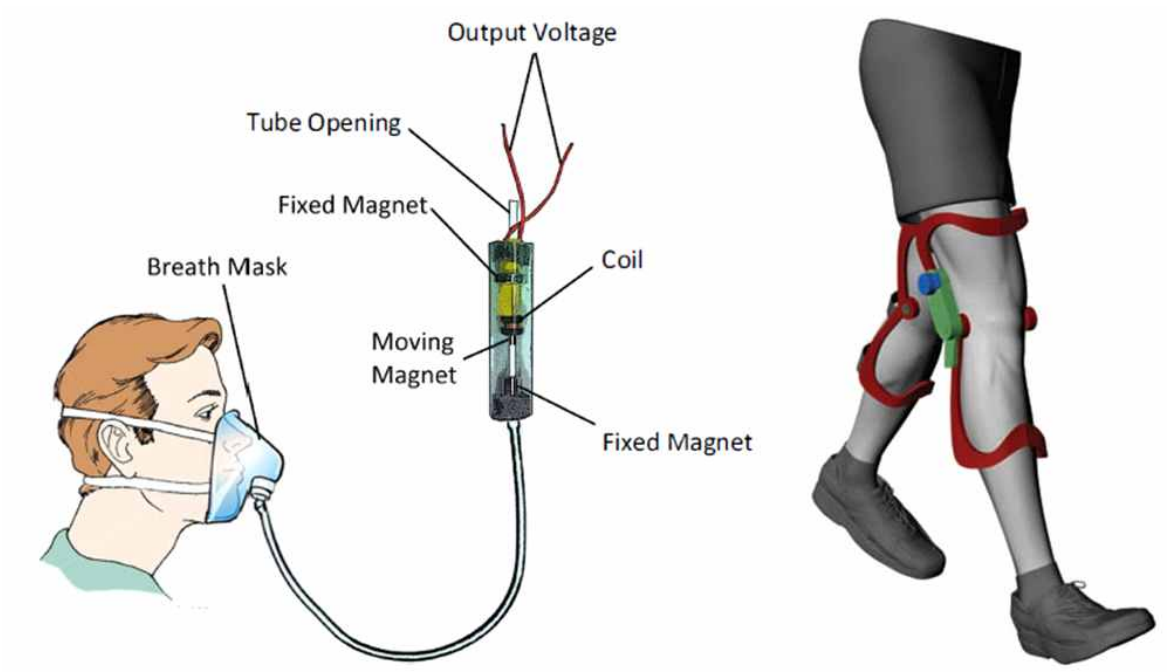

Figure 2.4 Various energy harvesting generating electricity during walking.

To transmit power wirelessly, a pair of coils resonating at a certain frequency can be used to implement magnetic resonant coupling. These coils are made of high-conductivity wires. Power transmission can be made more convenient by integrating the resonant coils into clothing; however, many problems can arise during such integration. Resonant coils can be integrated into clothing through a flexible printed circuit board (PCB); however, such circuit boards are much less flexible than fabric and therefore may cause discomfort to wearers. Wearable passive devices, such as woven inductors and antennas have been developed using conductive yarn, as shown in Figure 2.5 [16]-[17].

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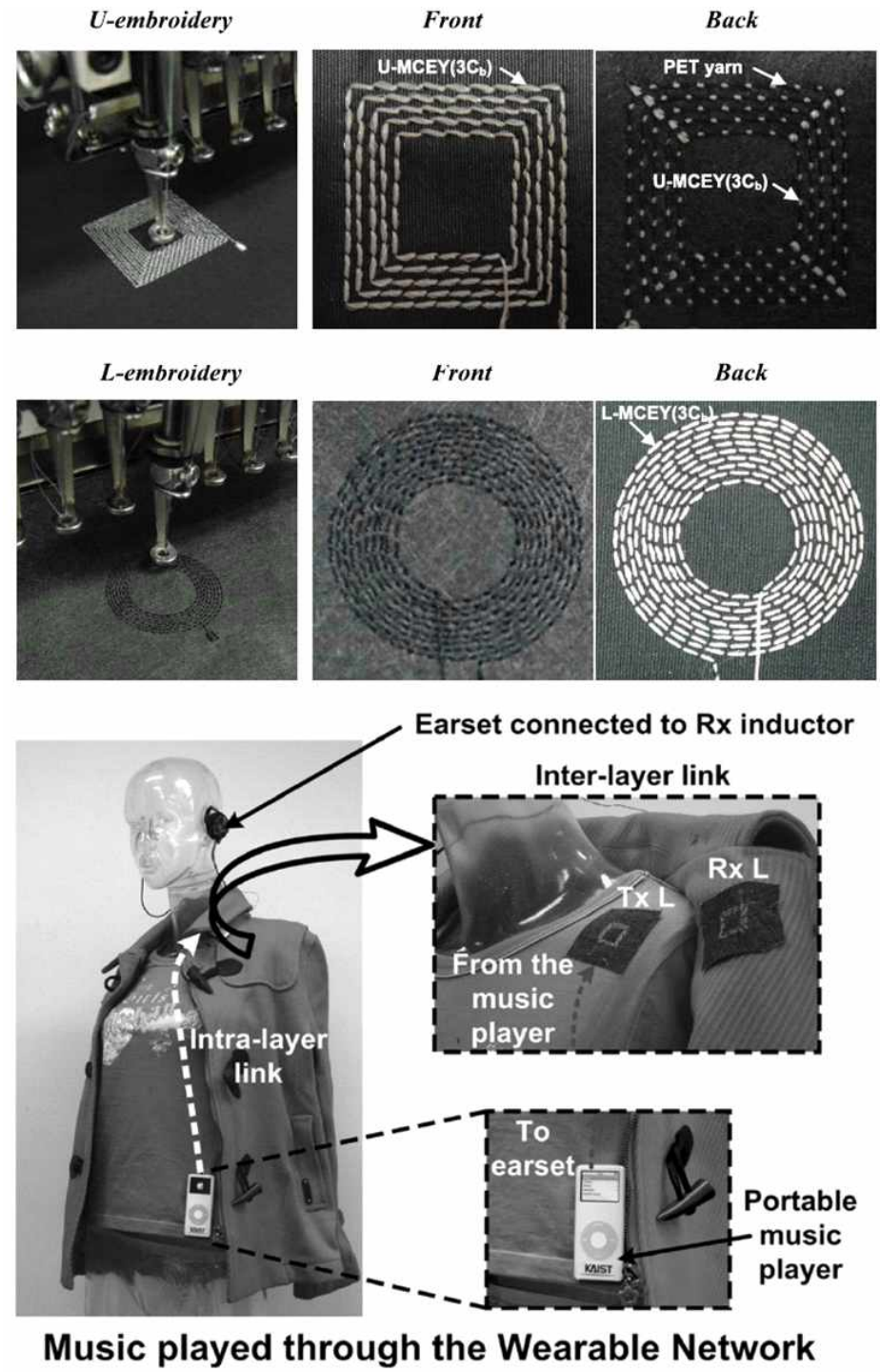

Figure 2.5 Woven inductors and antennas using conductive yarn.

Conductive yarn is integrated into clothing more easily than conventional flexible PCBs; hence, it is a material that is suitable for fabricating resonant

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coils for wireless power transmission. Unlike a conductive wire and flexible PCB, resonant coils made of conductive yarn do not affect clothing comfort.

B. Energy harvesting technology

Meanwhile, body-worn monitoring sensors have been developed to obtain and evaluate data from the human body. Several mobile healthcare applications have been developed for use by patients suffering mostly from lifestyle-oriented diseases. However, mobile devices have a limited battery life and require wireless charging and self-powered sensor systems in real time, as shown in Figure 2.6 [18].

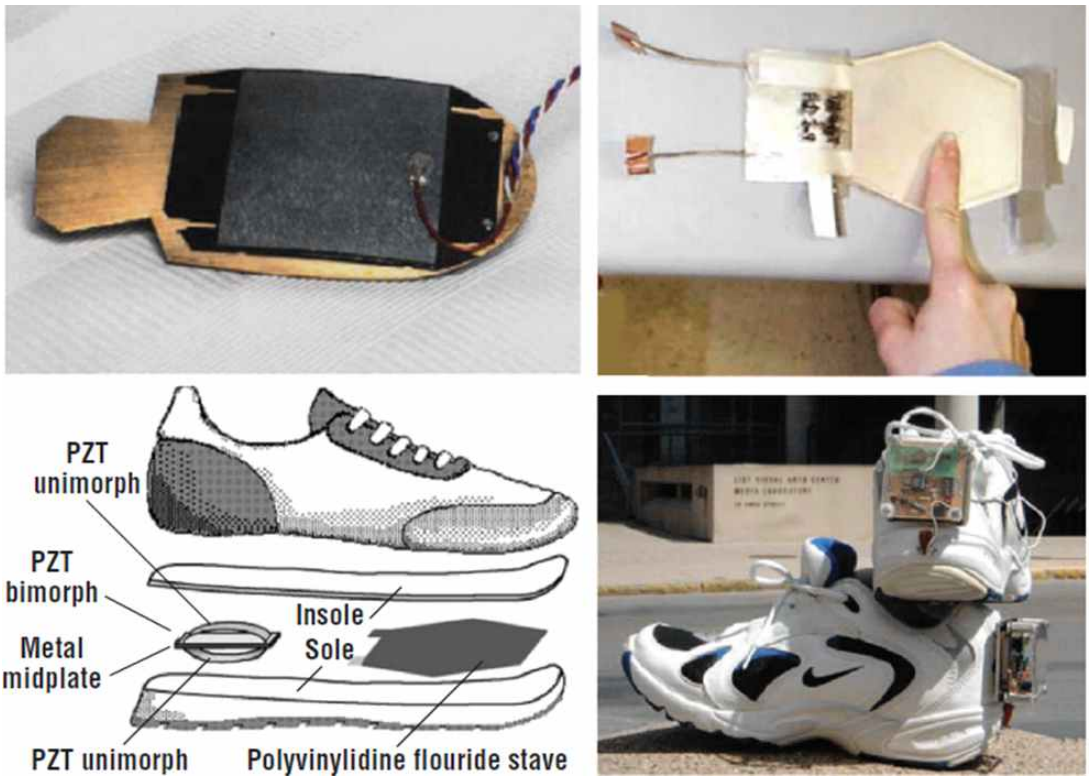

Figure 2.6 Integration of piezoelectric elements beneath a standard running sneaker's removable insole.

Hence, energy harvesting technologies have been proposed for overcoming the battery life limitation of mobile devices as shown in Figure 2.7 [19]-[20].

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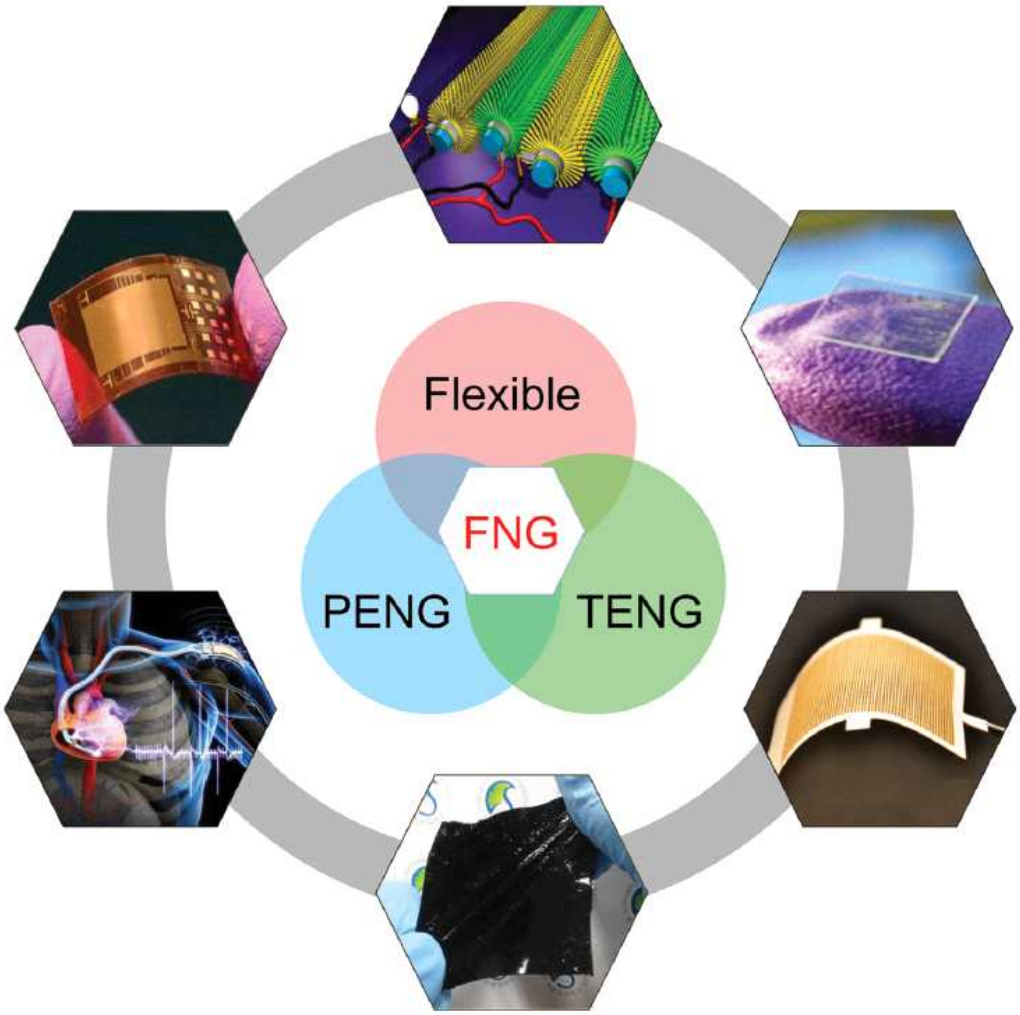

Figure 2.7 Energy harvesting technologies using flexible electronics, piezoelectric, triboelectric, and hybrid nanogenerators.

These technologies use piezoelectric [21]-[22], thermoelectric [23]-[24], and electromagnetic generation [25]-[26], and are applied according to the target environment. However, power generation by these methods is practically not sufficiently large for effective use. In recent years, triboelectric generators (TENGs) have been developed for harvesting energy from body movement and have a simple structure as shown in Figure 2.8 [27]-[29].

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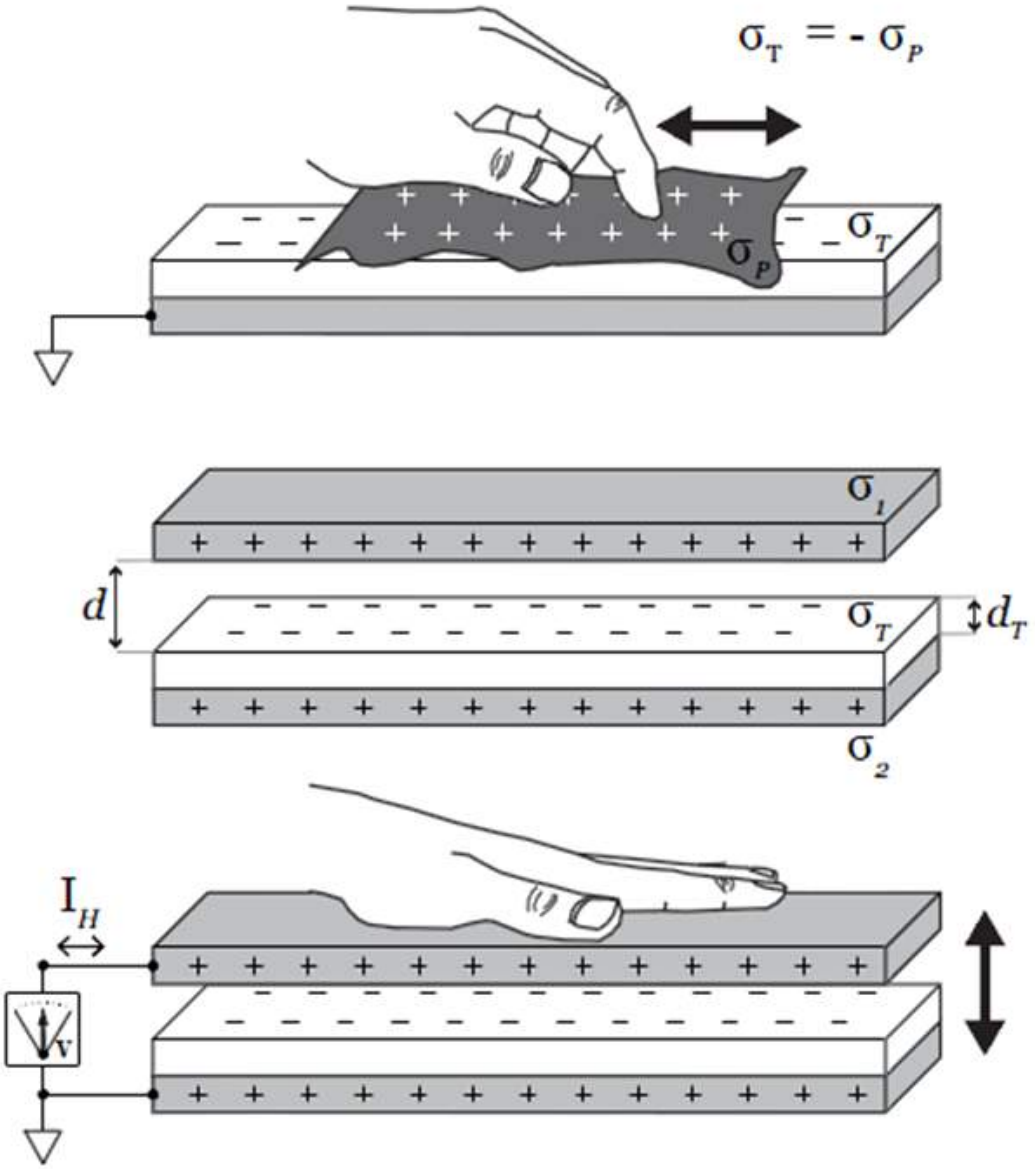

Figure 2.8 Energy harvesters touching, rubbing, and sliding to generate electrical energy.

A TENG consists of two materials that are oppositely charged, and an electrode that generates external current and can be used directly on the human body [30]-[31]. Triboelectrification is conventionally known since the ancient Greek era and usually taken as a negative effect. However, tactfully based on a conjunction of triboelectrification and electrostatic induction, triboelectric nanogenerator (TENG) is invented recently, which could convert

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mechanical energy into electricity as shown in Figure 2.9. Considering triboelectrification ubiquitously exists in the surrounding environment and for any most common materials used every day.

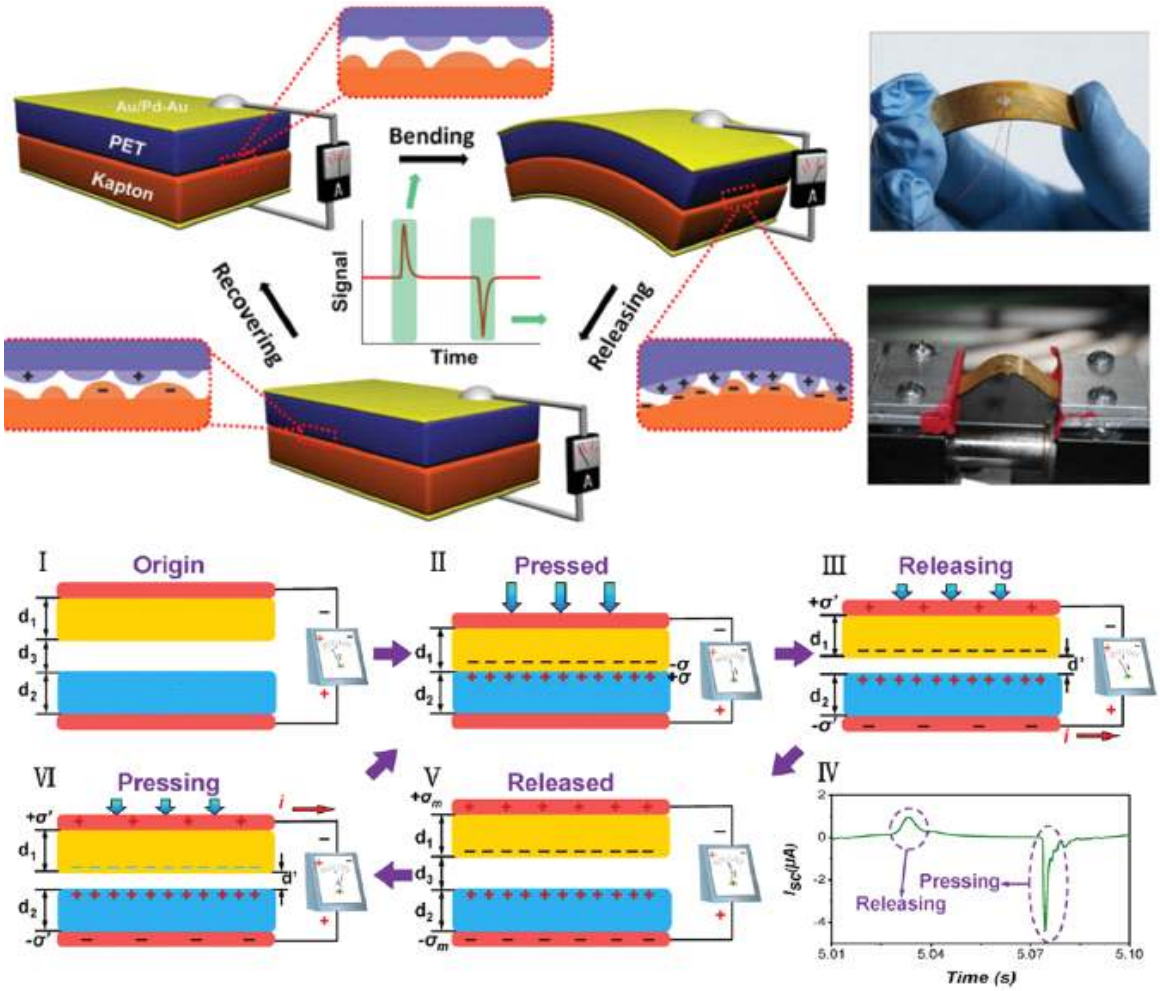

Figure 2.9 Invention and working principle of the flexible triboelectric nanogenerator.

Fiber-based FTENGs can convert mechanical energy generated from body motion into electrical energy and can be easily integrated with clothing [32]-[33]. A new type of fiber-based single-electrode triboelectric nanogenerator (FSTENG) has been proposed that uses silicone rubber as the negative part and a conductive thread as the electrode, as shown in Figure.

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2.10 [34]. The electrical output is generated by the continuous contact and separation between human skin and silicone rubber.

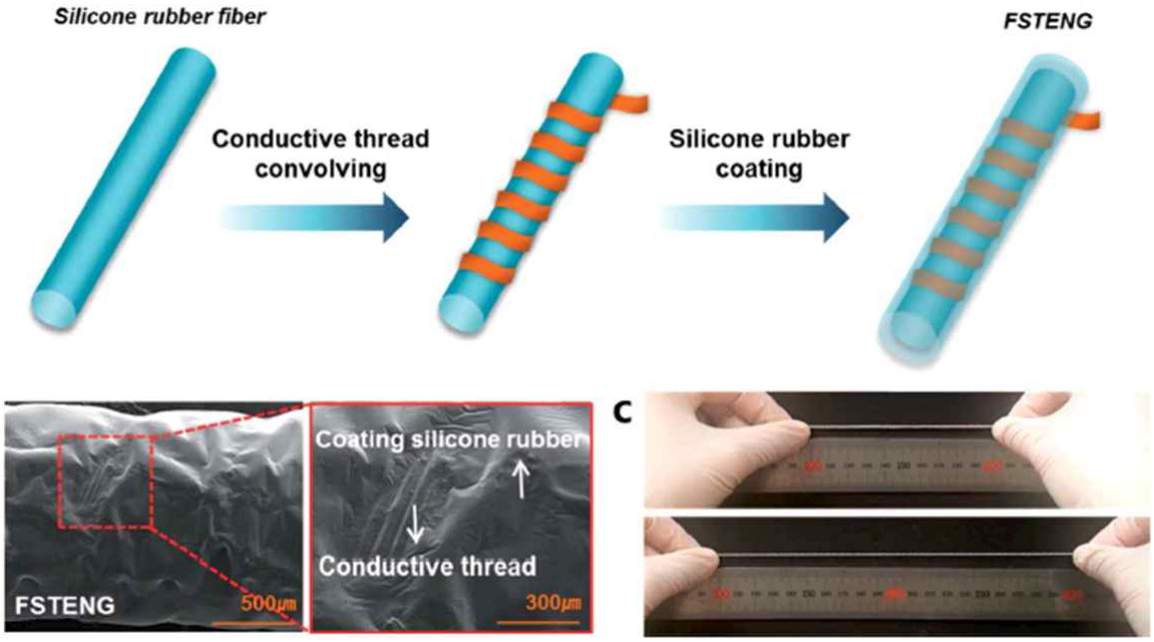

Figure 2.10 Structure and manufacture process for FSTENG.

The generated power is transmitted wirelessly for various applications, such as between outer and inner clothing and between sleeves and band-shaped sensors. This wireless charging method based on textiles can be used for harvesting and storing energy from body movement. To store and use the energy, a supercapacitor and battery can be converted into fabrics using carbon-nanotube fibers, which enable the fabrication of wearable energy storage, as shown in Figure 2.11 [35]-[36].

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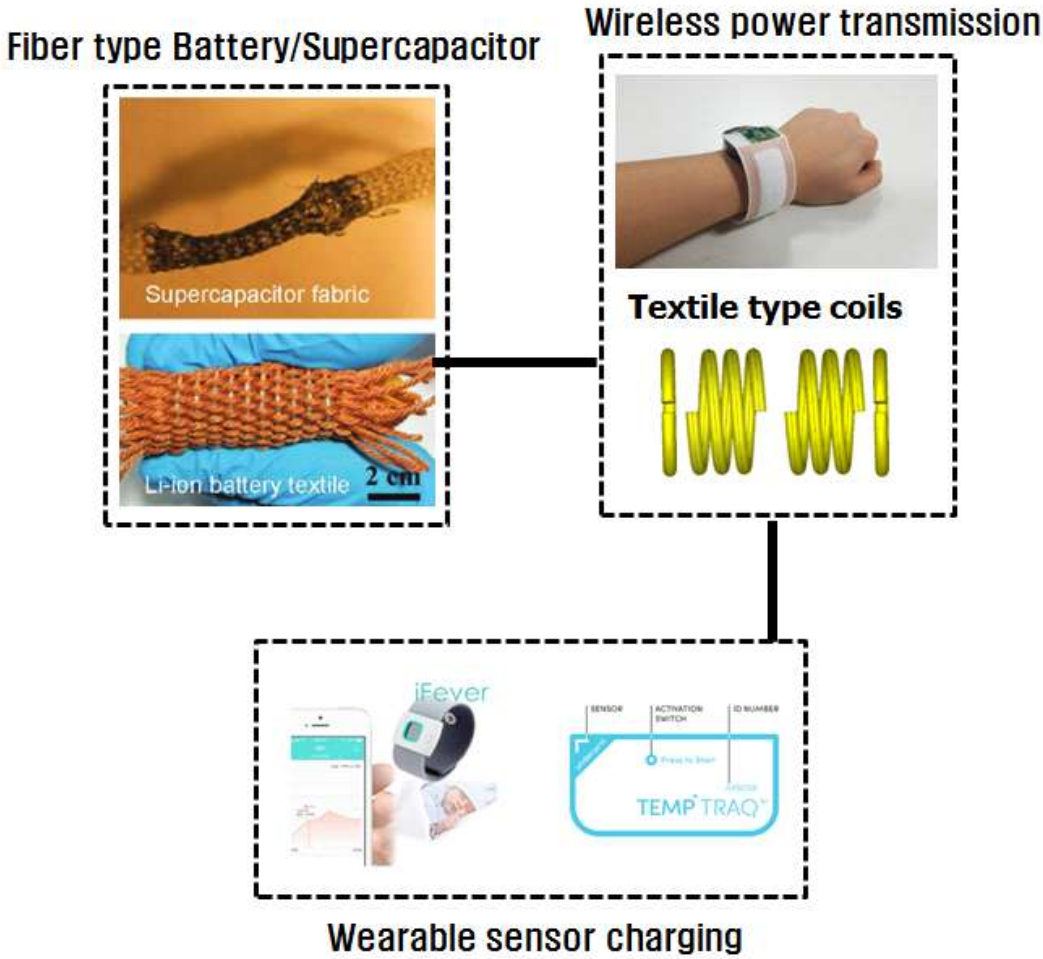

Figure 2.11 Application structure for wireless power transmission using supercapacitor and battery made of fabric.

The fabric energy storage can be integrated into clothing with a copper wire resonant coil for wireless charging [37]; however, the resonant coil causes discomfort to wearers and the stored power should be wirelessly transmitted to charge a body-worn sensor during movement.

C. Wireless power transmission

Although research on wireless power transmission technology began about 100 years ago, research was first carried out to supply high-power electricity wirelessly to long-distance wireless power transmission and buses on the

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road [38]-[39]. In 2007, the research result of the wireless energy transmission method using magnetic resonance was announced and the popularization of the smartphone rapidly raised the interest of wireless charging technology. Especially, as the usage time of smart phone increases, consumers who feel the inconvenience of frequent recharging of battery are offering opportunity to change the dominance of smartphone market by launching smartphone with convenient and safe wireless charging function. Based on this, wearable and IoT devices including smart watches are also making efforts to secure a market. As shown in Figure 2.12, the demand for electric vehicles is steadily increasing reflecting the burden of using fossil fuels and the social atmosphere that emphasizes eco-friendliness, and automobile manufacturers are developing technology to develop wireless charging technology more convenient [40]-[42].

Figure 2.12 Wireless power transmission for electric car.

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As shown in Figure 2.13, Sivantos, a multinational hearing aid manufacturer that has acquired Siemens' hearing aid business, launched 'Primax Cellion', a hearing aid that incorporates wireless charging technology, and is available 24 hours a day for 4 hours charging. And the inconvenience of replacing the battery every once in a while [43].

Figure 2.13 Wireless chargeable hearing aid.

Until now, the wireless charging techniques have been limited to the spatial freedom of the transceiver for charging as a two-dimensional transmission system, and three-dimensional space wireless charging techniques for overcoming this have been developed. Especially, as shown in Figure 2.14, 'E-Cup' recently developed by Korea Electronics and Telecommunications Research Institute (ETRI) adopts the technique of forming a uniform field in a space although it is a small space, so that a small receiver such as a smart phone can achieve uniform efficiency Which can charge the battery [44].

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Figure 2.14 3D wireless charging system.

The wireless charging method can be used to wirelessly transmit power through disconnection while maximizing user convenience because the resonant coils required for power transmission are integrated into clothing. The resonant coil employed to transmit power comprises a sending coil and a feeding coil, which provides power to the sending coil. The feeding coil of the conductive yarn is connected using a printed circuit board (PCB). In the same way, the resonant coil employed to receive power a receiving coil and a feeding coil. The receiving and the feeding coils are mounted on a flexible PCB to receive power. The transmission characteristics of the resonant coils are measured and compared with simulation results. For obtaining simulation results, the resonant coil was modeled under various conditions, which were simulated for signal loss and resonant frequency using a commercial simulator CST (Computer Simulation Technology) to analyze electromagnetic structures.

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III. Key idea

A. Wireless power transmission using textile

The key purpose of this research is to show feasibility of converging wireless power transmission to wearable electronics. The proposed wireless power transmission method provides simple but reliable results. The idea of wireless charging can also provide great value to the smart fashion market. Smart fashion can incorporate electronic devices, including small computers, into clothing. Many researchers have conducted research combining smart fashion and data communications.

As a result, various communication devices such as antennas, resistors and transistors have been developed in the form of smart textiles. In addition, wireless power transmission technology using resonant coils and energy harvesting technology are continuously being studied. However, little progress has been made in wireless charging technology for devices used in smart fashion.

The technology presented in this thesis can be used to transmit power wirelessly between sleeves and ankles and between outer and inner garments while the resonant coils needed for wireless power transmission are embroidered on the garment to maximize user comfort. We also studied textile-type wireless power transmission technology that can be applied to various applications including motion by designing the resonance frequency of the resonant coil according to the changed coil length after the embroidery of the conductive material to the fabric in the human body wearing condition.

Energy harvesting devices that harvest energy from the movement and friction of the human body are also being developed in various textile forms. Thus, energy can be harvested anywhere where clothing can be worn on the human body. When a textile type coil is worn on a shoe in which the kinetic energy of the human body is greatest, the energy harvested from the energy

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harvesting device integrated in the shoe can be wirelessly transmitted to the pants. The transmitted energy can charge the mobile device located in the pants pocket and power the bluetooth key tracker, GPS control, smart belt and so on. The friction energy harvested between the elbow and the body can also be wirelessly applied to the smartring, smartfinger, smartbracelet, smartwatch, smartshirt with heart & respiration sensors incide using a textile coilf. The more wearable technology develops, the more wearable devices increase. However, if all the wearable devices are operated by the battery, it may cause discomfort to the wearer. Thus, advances in textile-type wireless charging technology are essential to implement all the processes for harvesting, transferring and operating energy into textiles.

The technology of harvesting energy by the movement of the human body still produces weak electric power for real life, but it is continuously improving with the development of nanotechnology. Therefore, if the technology that can conveniently supply the harvested energy wirelessly is established, the wearable device market is expected to spread rapidly. However, it is not as easy as it is to develop a technology that supplies energy in the form of textiles for commercialization and mass production. Textiles are not as accurate as electronic circuits. It is important to minimize the error range and ensure that the wireless charging is within the realizable range.

In this paper, the same sized textile coils were fabricated and measured by simulation. The textile-type coils fabricated and measured over 5 times has resonance frequency error range within 0.5 MHz and signal loss error range within 0.5 dB. The transmission efficiency of the wireless charging was affected more by the wearing condition and movement of the human body than the error range of the manufactured resonance coil. However, since it shows a certain change in average transmission efficiency, the feasibility of wireless charging commercialization technology can be expected in the future.

Drawbacks to wireless charging for wearable device are lower efficiency, slower charging and uncomfortable fit, which will be improved by newer coil

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structures. Most wearable devices are extremely low-powered, meaning the impact of these drawbacks may be minimal.

In order to achieve wireless charging in a real life, the user needs to charge in a state of unconsciousness. A system that can not feel fit is essential for wireless charging in everyday life that does not move or move the body. A wireless power transmission using textile that is free of design and easy to wear can be applied to various wearable devices as shown in Figure 3.1 [45].

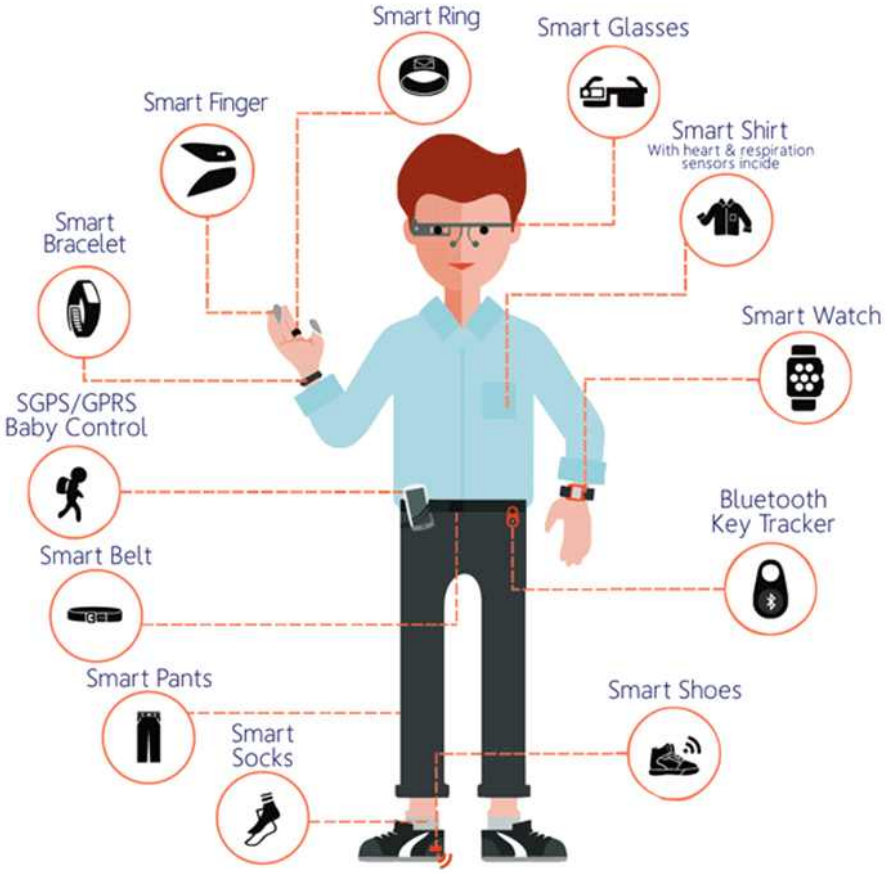

Figure 3.1 Wearable devices

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IV. Experiment and result

A. Transmission characteristics of the resonant coils of conductive yarn

To investigate the feasibility of using conductive yarn for wireless power transmission, the transmission characteristics of resonant coils made of conductive yarn were compared with those of resonant coils made of copper wire through simulation and measurement [46]-[47]. The conductive yarn in this study was made of Ag-plated copper wire and polyester yarn, as shown in Figure 4.1 [48]-[49].

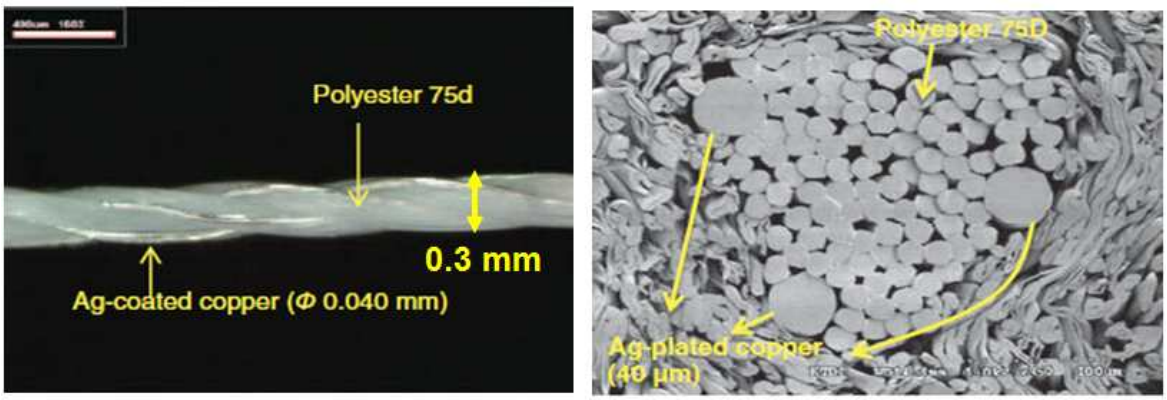

Figure 4.1 Structures of conductive yarn: SEM images.

A silver-plated copper filament of 0.040-mm-diameter was wrapped around a strand of polyester yarn of 75 denier with 150 T/m (twists per meter); the copper filament wrapped the polyester yarn was then twisted with 700 T/m. Finally, three strands of the twisted yarn were piled together with 550 T/m; the resulting conductive yarn had the density of 547 denier and the diameter of 0.3 mm, as shown in Figure 4.2.

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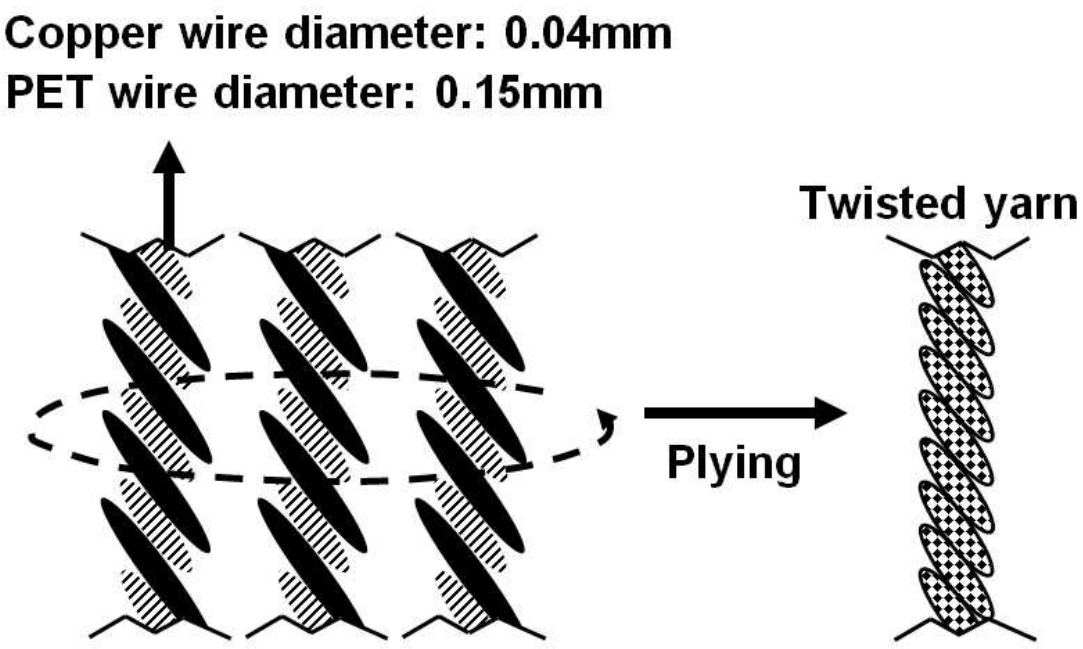

Figure 4.2 Structure of twisted yarn.

Due to such a twisting structure, part of the copper wire was exposed on the surface of the conductive yarn; hence, the conductive yarn touches the skin after being integrated into clothing and, accordingly, current leakage to skin could occur. The conductive yarn, however, maintains insulation from the skin because the exposure area of the copper wire is insignificant. The measurement results on resistance of the conductive yarn showed that the resistance was 0.0925 Ω/cm and almost the same, 0.0895 Ω/cm, even after the conductive yarn was touched by the hand. Therefore, the transmission characteristic of the resonant coils is not significantly affected by the skin contact of the conductive yarn. The signal losses of the conductive-yarn resonant coils were simulated after modeling the conductive yarn with an 86.2-μm-diameter copper wire. This model was reasonable because the polyester yarn does not contribute to power transmission owing to its low conductivity; further, the three strands of Ag-plated copper wire were equivalent to a signal wire having a diameter of 86.2 μm. For comparison with the resonant coils made of conductive yarn, resonant coils made of 0.5-mm-diameter copper wire were measured and simulated.

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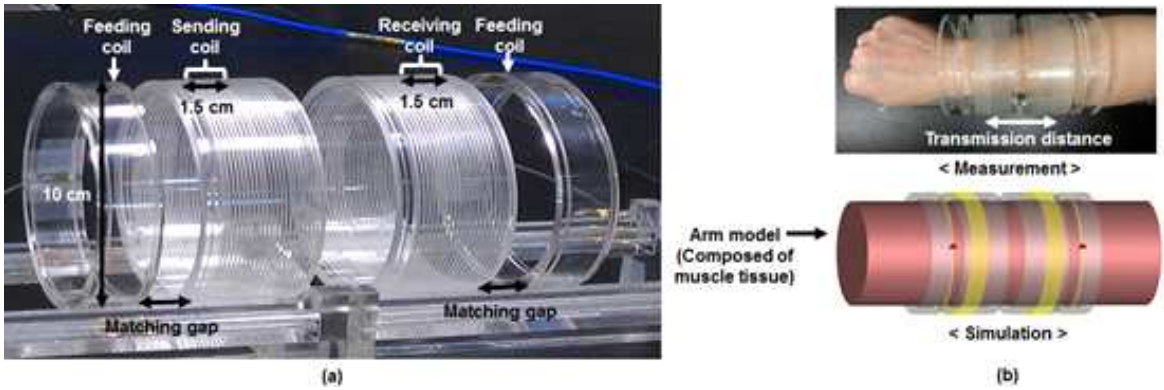

Figure 4.3 (a) Structure of resonant coils and (b) measurement and simulation.

Figure 4.3 (a) shows the structure of the resonant coils. The resonant coil to transmit power was composed of the sending coil and the feeding coil, which provided power to the sending coil. In the same way, the resonant coil to receiver power was composed of the receiving and the feeding coils. As shown in Figure 4.3 (b), the conductive yarn or copper wire was wound around a Plexiglas fixture with a diameter of 10 cm during the measurement. The Plexiglas fixture contained grooves to fix the coil shape and the gaps between the conducting lines. The number of coil turns determines a resonance frequency. It increases as the number of coil turns increases and, accordingly, length of the resonant coils becomes longer. The number of coil turns was designed to have the resonant frequency of 6.78 MHz or 13.56 MHz, which is included in the industrial, scientific, and medical (ISM) band. The lower resonant frequency of 6.78 MHz, however, caused the large number of coil turns and wide width of the resonant coils, which was 50 turns and 7.5 cm respectively. This is because the resonant frequency is inversely proportional to the number of coil turns, which determines the length of the resonant coils. In this study, the resonant coils had 10 turns considering integration with clothing. The resonant frequency of the sending and receiving coils was 21.82 MHz, but it decreased to near 13.56 MHz after the resonant coils of the conductive yarn were embroidered on the polyester

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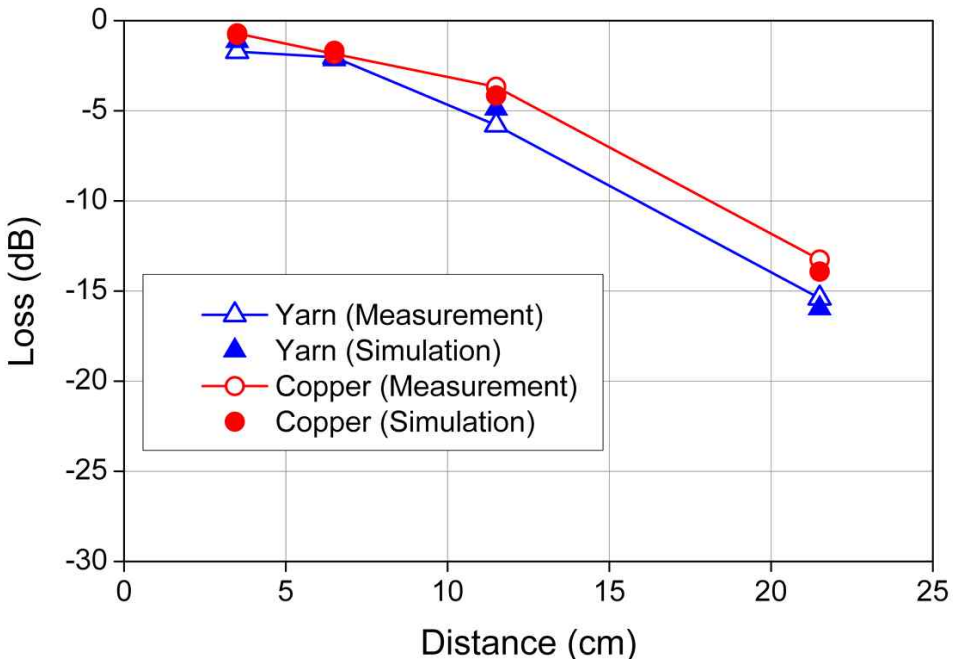
fabric, which will be explained in the next section. The number of feeding coil turns and the matching gap were selected for impedance matching [50]. As shown in Figure 4.3 (b), the signal loss was measured with the arm inserted inside the resonant coils; it was also measured without the arm. For the simulation, the human body was modeled as a cylindrical muscle tissue with a diameter of 8.5 cm, which was measured with respect to the arm of the human subject, as shown in Figure 4.3 (b). The signal loss was simulated using CST to analyze electromagnetic structures. In this study, the transmission distance between the sending and the receiving coils was defined as the distance between the center of the sending and receiving coils, as shown in Figure 4.3 (b).



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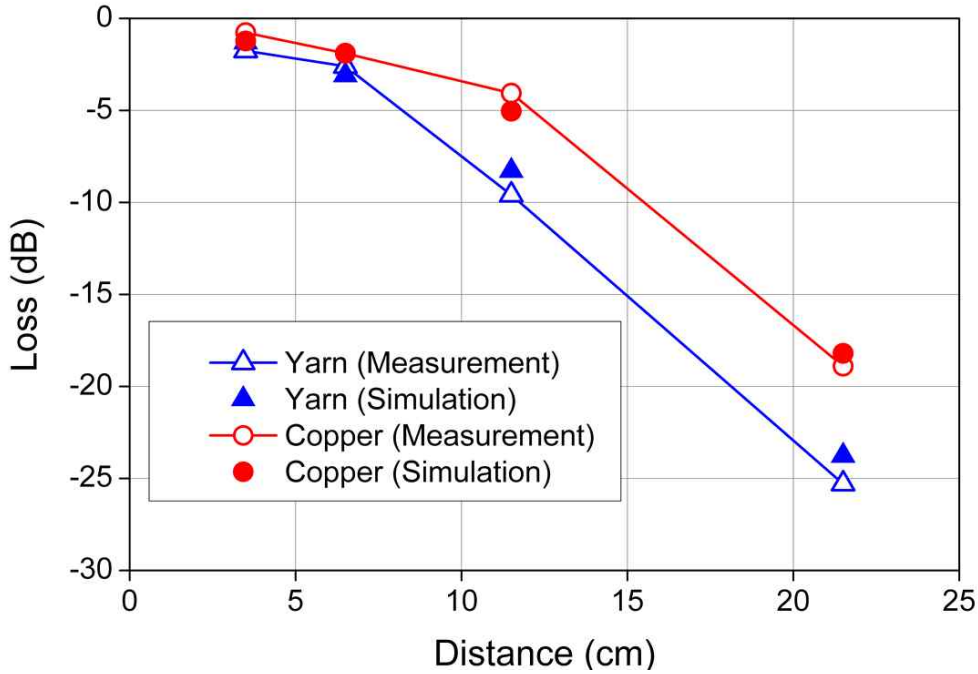

Figure 4.4 Measurement of signal losses and comparison with simulation results (a) without a human body in the transmission path and (b) with a human body in the transmission path.

Figure 4.4 (a) shows the measured signal losses of the resonant coils made of copper wire and of the resonant coils made of conductive yarn as well as the comparison with the simulation results. In this thesis, the signal loss is defined as the ratio of input and output power, in which the input power is measured or simulated at the feeding coil for the sending coil while the output power at the feeding coil for the receiving coil. The signal losses were measured and simulated with different transmission distances between the coils. The measurement and simulation results of the signal losses were almost identical. The signal loss increased with an increase in the transmission distance. The signal loss of the conductive-yarn resonant coils was higher than that of the copper-wire resonant coils because the copper wires in the conductive yarn had a very small diameter, and hence, a large resistance loss. However, the coupling coefficient between the sending and receiving coils was high when the transmission distance was less than 6.5 cm. Thus, the signal loss difference between the resonant coils consisting of

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copper wire and the resonant coils consisting of conductive yarn was less than 1 dB. The proposed conductive-yarn resonant coils were integrated into clothing to keep the human body in the transmission path [51]. Hence, it was necessary to consider the effects of a human body on the signal loss. The signal losses were measured using the measurement setup shown in Figure 4.3 with an arm inserted inside the coils. Figure 4.4 (b) shows the measurement results. The resonant frequency of the sending and receiving coils changed slightly when an arm was inserted; hence, the matching gap of the feeding coils was controlled for impedance matching. When a human body was in the transmission path, the increases in the signal losses of the resonant coils made of copper wire and conductive yarn were as small as 0.06 and 0.57 dB, respectively, at a transmission distance of 6.5 cm. This is because the human body does not affect the magnetic resonant coupling in the sending and receiving coils. However, the coupling coefficient was reduced when the transmission distance was increased to more than 6.5 cm, and the presence of a human body further increased the signal loss.

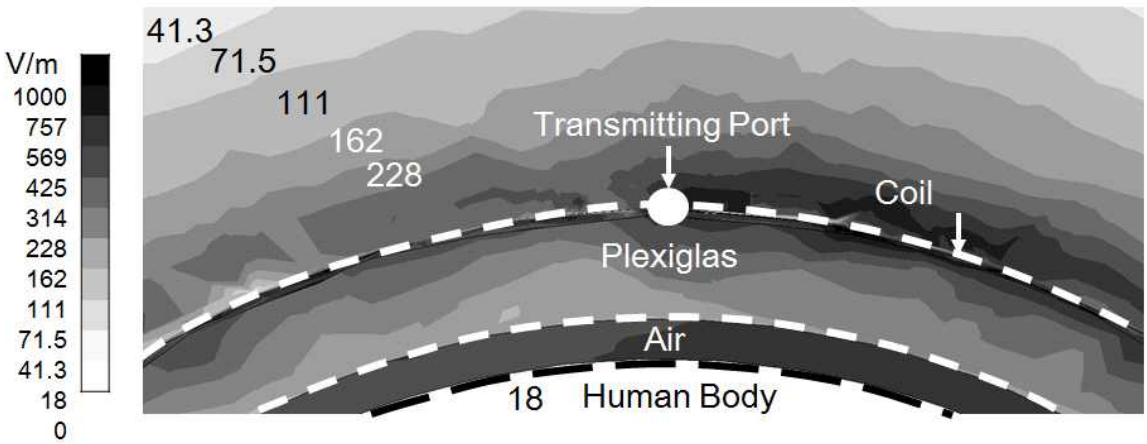

Figure 4.5 Electric field distribution around a human body.

Figure 4.5 shows the simulation results of the electric field distribution around a human body and resonant coil. The input power of the resonant coil was 5 dBm at 21.82 MHz. The simulation results show that the maximum

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strength of the electric field was 18 V/m inside the coils. When the human body is exposed to an electromagnetic wave, the maximum allowable strength of the electric field strength is 28 V/m between 10 MHz and 400 MHz [52]; hence, power up to 5 dBm can be transmitted using resonant coils when a human body is in the transmission path. Outside the resonant coils, the electric field strength decreased rapidly with an increase in the distance from the resonant coils, in contrast to the behavior inside the coils.

B. Application of conductive-yarn resonant coils

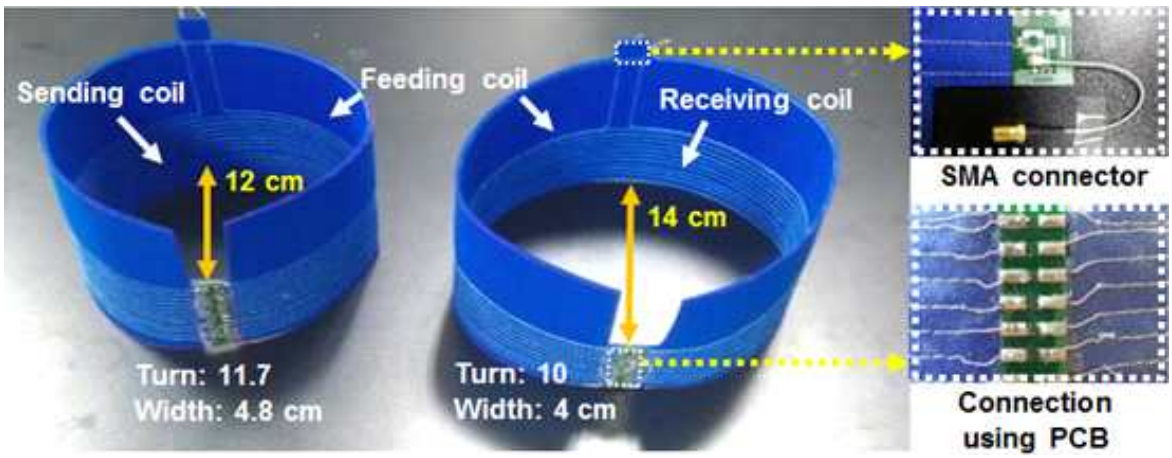

Figure 4.6 Resonant coils made of conductive yarn embroidered on nonwoven polyester fabric.

Human-activity-based energy harvesting technology collects energy from the motion of joints, pressure from heel strikes, or weight shifts that occur at insoles during walking [53]-[55]. After the energy from the heel strike pressure or the weight shift at an insole is collected, it is wirelessly transmitted from shoes to trouser cuffs. It can then be used to charge a battery. In this study, conductive-yarn resonant coils were applied to achieve such power transmission. The transmission efficiency was measured after positioning the sending and receiving coils around the shoes and trouser cuffs, respectively, of a human subject. Here, conductive-yarn resonant coils

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with different diameters were fabricated, as shown in Figure 4.6 The sending coil located around the ankles had a diameter of 12 cm, and the receiving coil located around the trouser cuffs had a diameter of 14 cm; each diameter was selected considering the perimeters of the trouser cuffs and the top sides of the shoes. The sending coil was 4.8 cm wide, with the number of coil turns being 11.7. The receiving coil was 4 cm wide, with the number of coil turns being 10 in order to eliminate the resonant frequency difference between the sending and receiving coils. The conductive yarn was embroidered on a 1-mm-thick polyester fabric of a felt type, and the edges of the conductive yarn were connected using PCBs. The signal loss of the conductive-yarn resonant coils was measured after the coils were fixed with Plexiglas fixtures. The coil diameters were larger than those shown in Figure 4.3, and the coil length of the conductive yarn increased when the conductive yarn was embroidered on the nonwoven polyester fabric; hence, the resonant frequency was reduced to 14.5 MHz, because the resonant frequency is inversely proportional to the coil length. The signal loss was 2.8 dB at a transmission distance of 0 cm, in which the sending and receiving coils completely are overlapped with each other according to the definition of the transmission distance.

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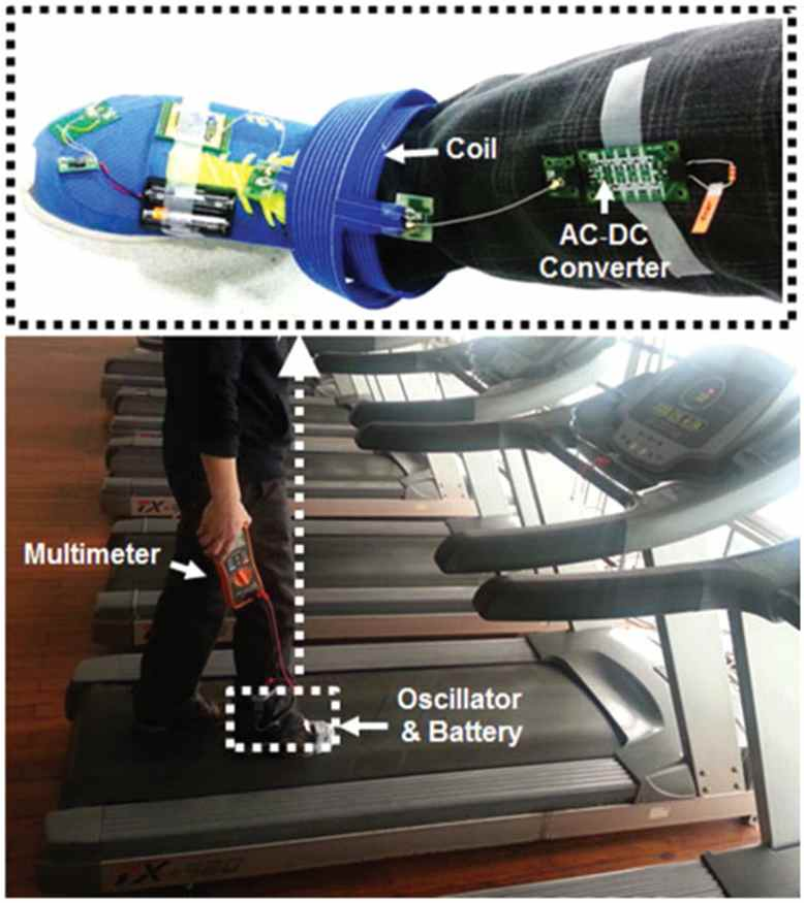

Figure 4.7 Setup used to measure the transmission efficiency when the subject was in motion.

Figure 4.7 shows the setup used to measure the transmission efficiency when the subject moved. The sending and receiving coils were positioned around the shoes and trouser cuffs, respectively. The transmitting signal was generated using an oscillator operated by a battery; the output power of the oscillator was 5 dBm. The generated signal was then input into the feeding coil for the sending coil. After being received at the feeding coil for the receiving coil, the receiving signal in an alternating-current (AC) type was converted into a direct-current (DC) voltage using the AC - DC converter, which had the conversion efficiency of about 70%. As the subject walked or ran on a treadmill, the DC voltage was measured using a handheld multimeter. The ratio of the DC output power at the AC-DC converter to the

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AC input power at the feeding coil for the sending coil, which is defined as the transmission efficiency, was 50% under optimal conditions, with the Plexiglas fixture attached to the resonant coils and a stationary subject.

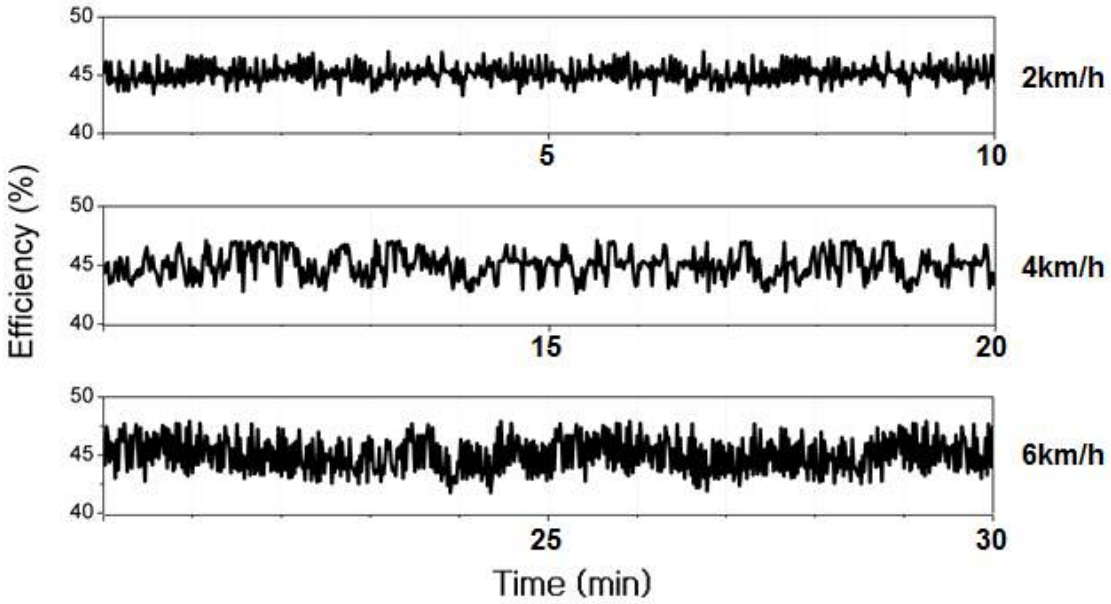

Figure 4.8 Change in the transmission efficiency as a function of body movement under (a) slow walking conditions, (b) normal walking conditions, and (c) running conditions.

Figure 4.8 shows the transmission efficiency when the subject was moving at various speeds. The treadmill speed was set first at 2 km/h, then at 4 km/h, and finally at 6 km/h. These speeds correspond to slow walking, normal walking, and running conditions, respectively. The transmission efficiency at each speed was measured for 10 min at 1-s intervals. The average transmission efficiency at all speeds was 45%, which is relatively high considering the conversion efficiency of to the AC-DC converter; the difference between the maximum and the minimum transmission efficiencies was 3.76% under the slow walking conditions, 4.46% under normal walking conditions, and 6.15% under running conditions; the variances in efficiency under each condition were 0.6%, 1.27%, and 2.24%, respectively, and the variance under the slow walking condition was the lowest. The reason for

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this difference is that the average movement speed was smallest under slow walking conditions; thus, the variations in the coil-shape change and alignment were the smallest. The average movement speed was the highest under running conditions; thus, the variance in the range of average transmission efficiency was the largest. However, the range of variation in the transmission efficiency was relatively small.

C. Transmission characteristics of the resonant coils of conductive yarn and flexible PCB

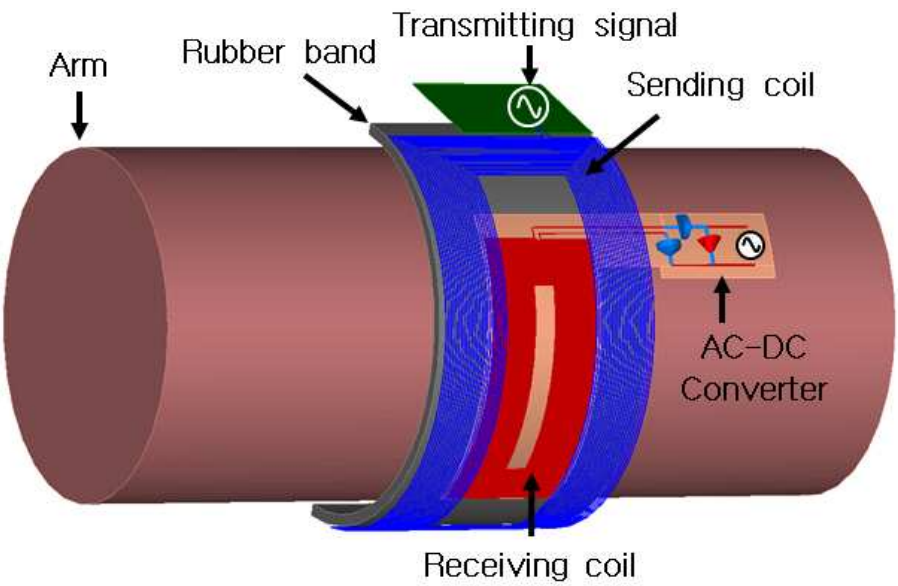

Figure 4.9 Structure of resonant coils.

Figure 4.9 shows the structure of the resonant coils on the human body. The receiving coil that is attached to a rubber band is on the arm overlapped by the sending coil. A transmitting signal was input into the sending coil. After being received at the receiving coil, the alternating current (AC) signal is converted into a direct current (DC) voltage using an AC - DC converter. The conductive yarn used in this study was made of polyurethane (PU)-coated copper wire and polyester yarn as shown in Figure 4.10 [56].

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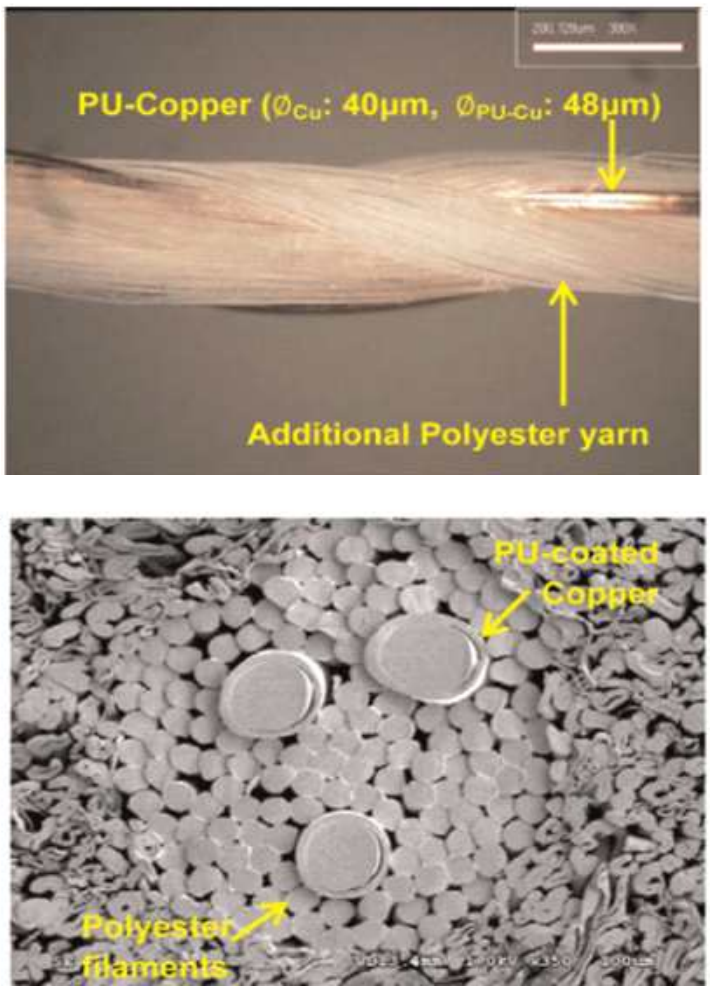

Figure 4.10 PU-coated copper wire and polyester yarn.

A PU-coated copper filament of diameter 0.040 μm was wrapped around a strand of polyester yarn of 75 denier. The copper filament was subsequently twisted at 700 T/m (twists per meter). The resonant coil was simulated after modeling the conductive yarn with a copper wire of diameter 86.2 μm. The three strands of copper wire are equivalent to a signal wire with a diameter of 86.2 μm. This model is reasonable because the polyester yarn and PU-coating do not contribute to power transmission owing to their low conductivity. Therefore, a sending coil with short line intervals maintains insulation owing to the PU-coated structure.

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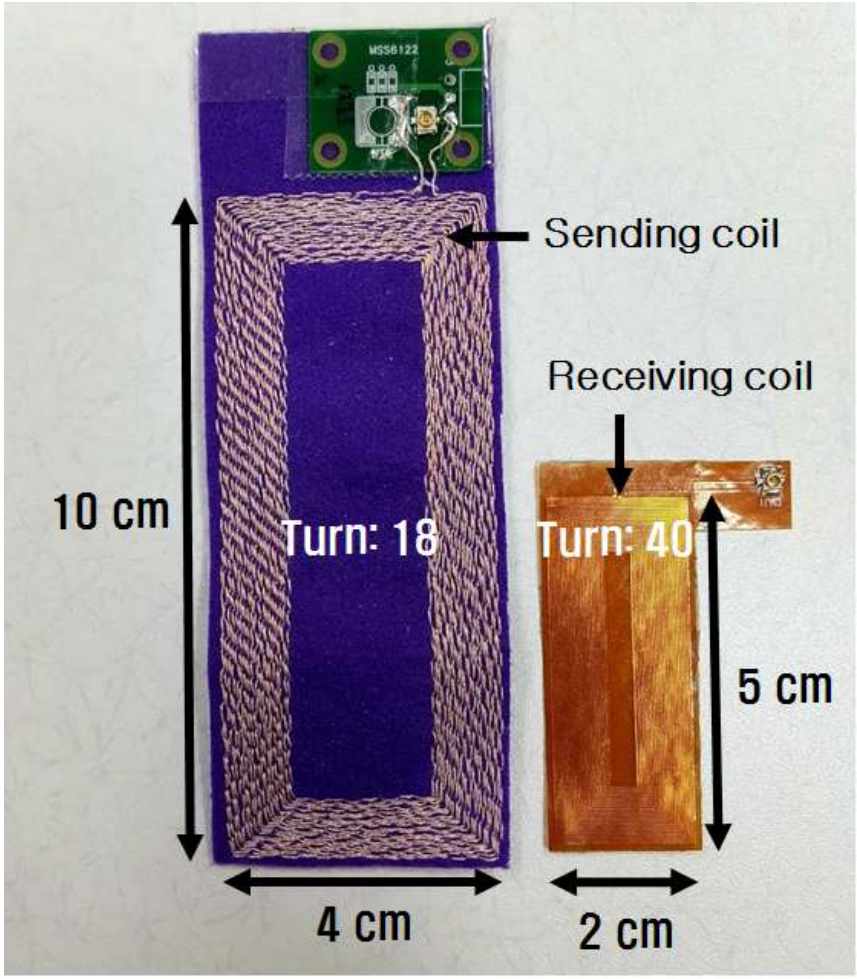

Figure 4.11 Resonant coils made of conductive yarn and flexible PCB.

The planar rectangular spiral resonant coils were fabricated with different sizes, as shown in Figure 4.11. Each diameter was selected considering the perimeters of the sleeves and the band-shaped sensors. The size of the receiving coil was 5 cm × 2 cm and the number of coil turns was 40 with 0.1-mm line intervals. The receiving coil was fabricated on a 0.2-mm-thick polyimide PCB with a 35-μm copper layer of thickness 0.1 mm. The size of the sending coil made of conductive yarn was 10 cm × 4 cm and the number of coil turns was 22.4 with 0.5-mm line intervals. The number of coil turns was designed to achieve a resonant frequency of 13.56 MHz to facilitate the use of the coil for applications, without disturbing potential surrounding communications. However, the resonant frequency of the sending coil

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decreased owing to the increased coil length after the conductive yarn was embroidered onto a 1-mm-thick felt-type polyester fabric. Hence, the increased coil length I must be subtracted from the simulated coil length O for determining the practical coil length P to be embroidered onto the fabric. The practical coil length P can be obtained from the increase of the coil length I, stitch intervals S, fabric thickness F, and simulated coil length O using equations

$$I = (P/S) \times (F/2) \quad (1)$$

$$P = O - I \quad (2)$$

Table 4.1. shows variables that compose the equation. The stitch interval S, fabric thickness F, length of simulated coil O, and the increase in coil length I were 2.5 mm, 1 mm, 5225.9 mm, and 870.9 mm, respectively. Thus, a sending coil with a practical coil length of 4354 mm was fabricated and the number of coil turns was 18. The measurement and simulation results of the resonant frequencies were almost identical, as shown in Figure 4.13.

In fact, the length increases to about 2.5 times when disassembling the embroidered conductive yarn to see the increased coil length. However, when measuring the change in inductance of a coil, it is difficult to analyze the correlation reflected in the coil because it measures the coil that is embroidered on the cloth rather than the actual conductive yarn. Therefore, the textile-type resonant coils was designed by calculating the increase in the length of the coil and the number of turns using equation with the exception of an impedance such as a coil inductance or capacitance. As the coil length of the sending and receiving coil increases under various conditions, the resonance frequency measurement result is almost the same as the simulation result. After compensating for length variations using an equation, the resonance frequency difference between the measurement and simulation results is less than 0.5 MHz. Therefore, the textile-type resonant coils can be designed using simple equations rather than complex correlation analysis.

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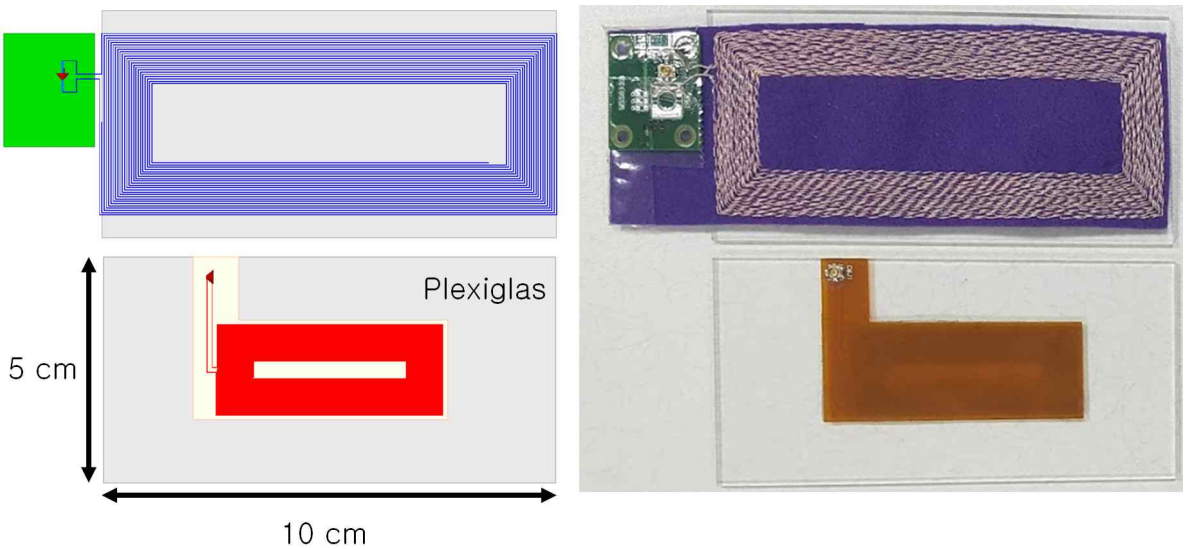
Table 4.1 Variables for compensating the change of coil length

Acronyms	Variables
O	Simulated coil length
I	Increased coil length
P	Practical coil length
F	Fabric thickness
S	Stitch intervals

D. Application of resonant coils being worn around the human body



(a)

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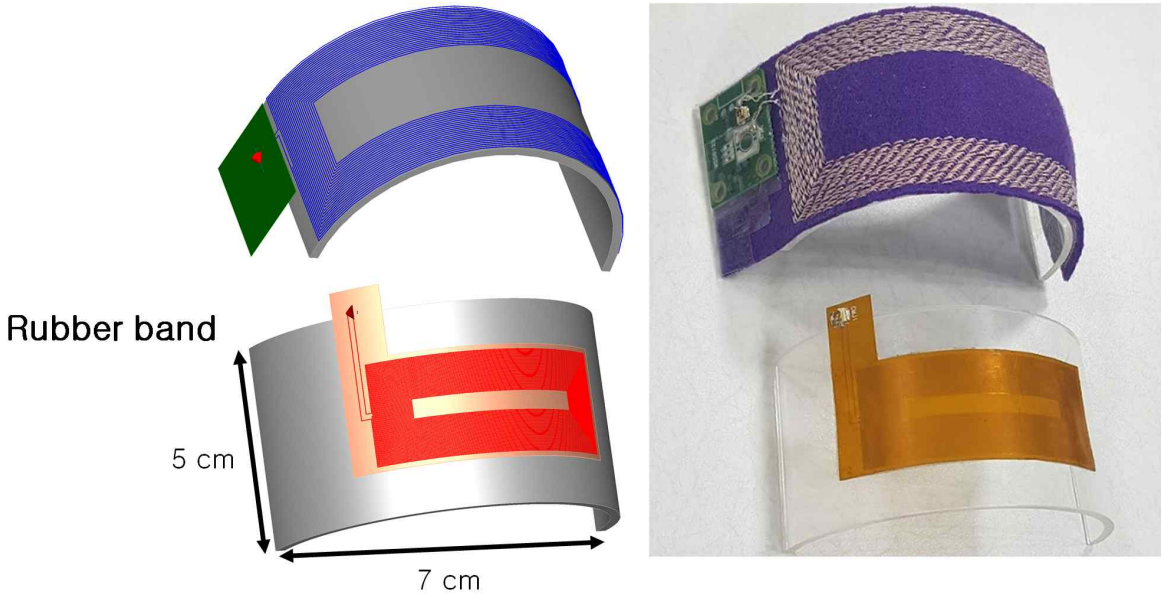
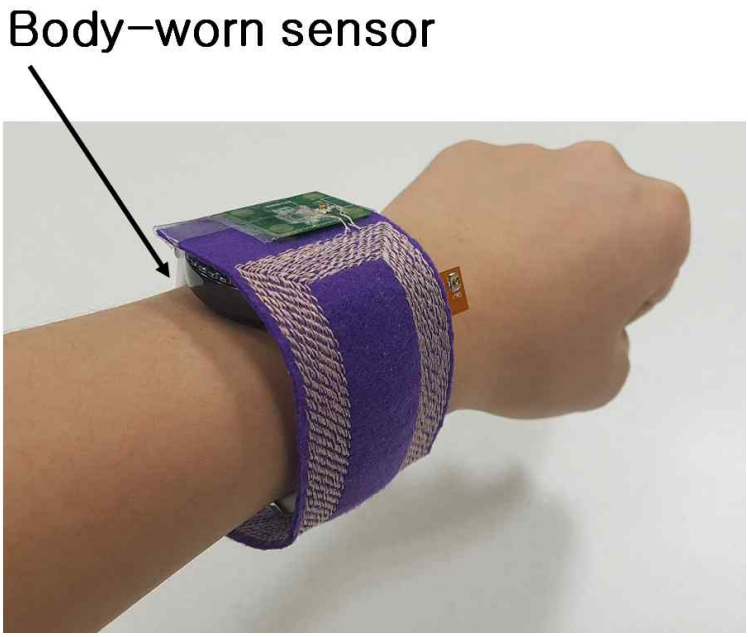


(b)



(c)

Figure 4.12 Resonant coil conditions (a) Flat coil with Plexiglas conditions, (b) bending coil with Plexiglas conditions, and (c) bending coil on body conditions.

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Figures 4.12 (a) and 4.12. (b) show the variation under flat and bending coil conditions using a Plexiglas fixture to fix the coil shape. For the simulation, the human body was modeled as a cylindrical muscle tissue with a diameter of 6 cm, which was measured with respect to the arm of the human subject, as shown in Figure 4.12 (c). When the coils were measured and simulated with Plexiglas, the resonant frequency decreased but remained unchanged between the flat and bending coil conditions owing to the almost constant values observed.

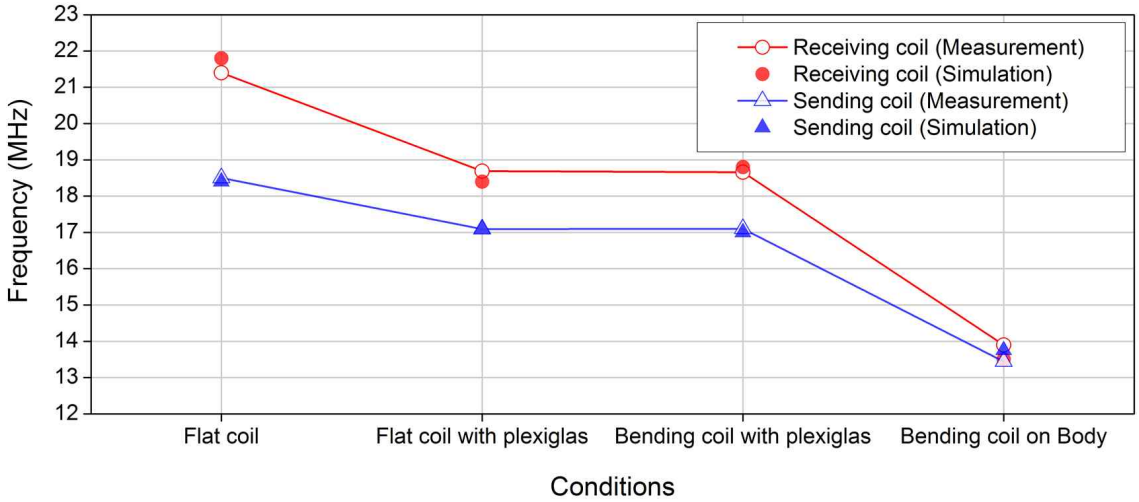

Figure 4.13 Measurement of resonant frequencies and comparison with simulation results.

Figure 4.13 shows the measured resonant frequencies of the sending and receiving coils, and the comparison with the simulation results. For comparison with the resonant coils made of conductive yarn and flexible PCB, the resonant frequency was simulated under various conditions. The length of the simulation model was determined based on the real length of the coils. The number of coil turns determines resonant frequency, which is inversely proportional to the coil length. However, the real resonant frequency of the sending coil decreased under flat coil conditions owing to the increased coil length, compared with the simulation. The measurement results on resonant frequency were almost the same with simulation results considering the

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increase in coil length of the sending and receiving coils under various conditions. After compensating the length change using equations, the resonant frequency difference between the measurement and simulation results was less than 0.5 MHz as shown in Figure 4.13. The measurement results of the resonant frequencies under flat coil conditions were 18.5 and 21.4 MHz as shown in Figure 4.11, but decreased to approximately 13.56 MHz with the arm, as shown in Figure 4.13. When the coils were worn, it was found that the resonant frequency of the receiving coil was less than that of the sending coil, since the resonant frequency of sending and receiving coils is proportional to the distance from the human body. Hence, the number of coil turns was designed to eliminate the difference between the resonant frequencies of the sending and receiving coils on the human body.

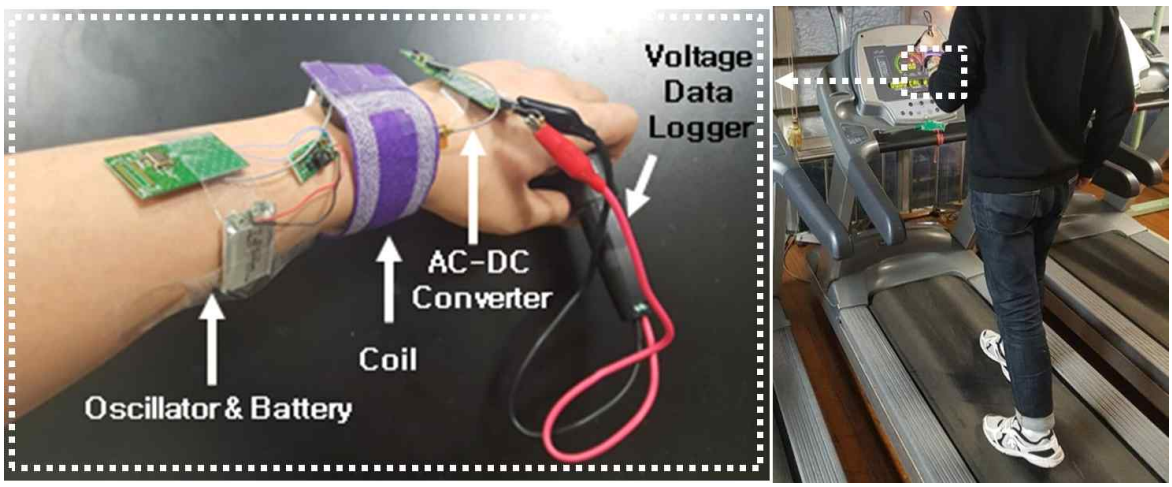

Figure 4.14 Measurement setup for body movement.

In this thesis, signal loss is defined as the ratio of input power to output power, wherein the input and output powers are measured or simulated at the sending and receiving coils, respectively. When the human body wore the sending and receiving coils along with a body-worn sensor, the measurement and simulation results of the signal loss were 2.57 and 0.82 dB, respectively. The signal loss obtained from the measurement was higher than that of the simulation because the resistance of the conductive yarn increased via the use

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of polyester yarn and the fabric in a practical embroidered condition. The signal loss was also affected by the eddy-current loss in the body-worn sensor. However, the difference between the signal losses obtained from measurement and simulation was only 1.75 dB. Figure 4.14 shows the setup used to measure the transmission efficiency during the movement of the subject. The sending and receiving coils were positioned around the arm. The transmitting signal was generated using an oscillator operated by a battery; the output power of the oscillator was 5 dBm. The generated signal was subsequently input into the sending coil. After being received at the receiving coil, the received AC signal was converted into a DC signal using the AC-DC converter, which had a conversion efficiency of approximately 70%. As the subject walked or ran on a treadmill, the DC voltage was measured using a USB-type voltage data logger. The ratio of the DC output power at the AC-DC converter to the AC input power at the sending coil, defined as the transmission efficiency, was 55.1% under optimal conditions, with the body-worn sensor attached to the resonant coils and a stationary subject.

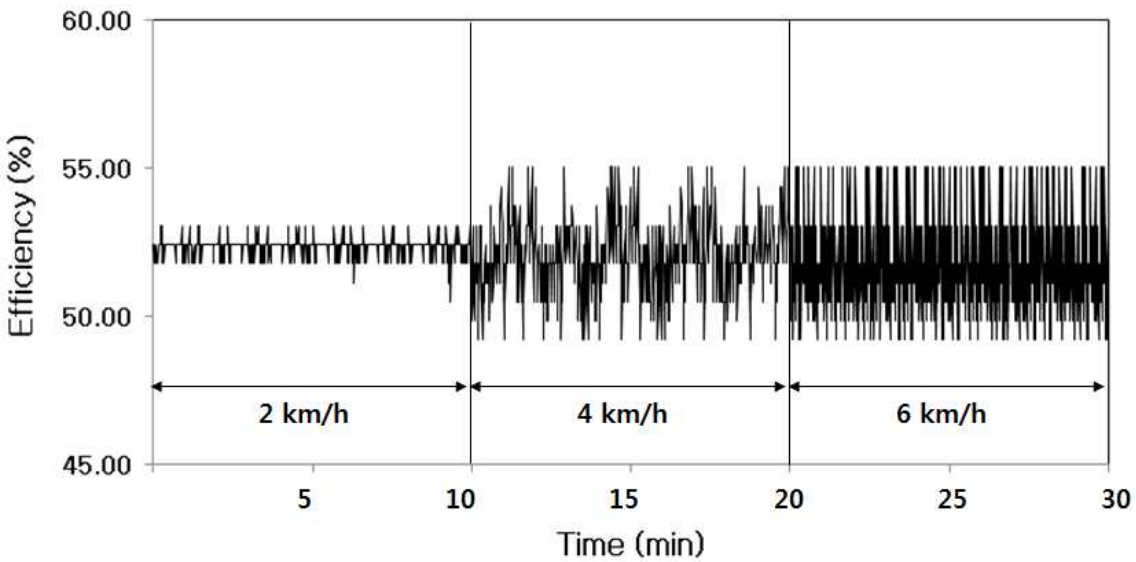

Figure 4.15 Change in the transmission efficiency as a function of body movement under moving conditions.

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Figure 4.15 shows the transmission efficiency when the subject was moving at various speeds. The speed of the treadmill was first set at 2 km/h, subsequently at 4 km/h, and finally at 6 km/h. These speeds correspond to slow walking, normal walking, and running conditions, respectively. The transmission efficiency at each speed was measured for 10 min at 1-s intervals. The average transmission efficiency at all the speeds was determined to be 52.1%. When the coils are fixed, the maximum transmission efficiency can be obtained. However, the variations in the coil shape change and alignment conditions occur during body movement. The change in the resonant frequency is proportional to the variations, thereby causing a change in the transmission efficiency. The variations in the coil shape and alignment under the slow walking condition were the smallest because the range of average movement speed was the smallest; thus, the variance in efficiency under the slow walking condition was the lowest.

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V. Conclusion

Textile-type resonant coils have been proposed for wireless power transmission in human activity-based energy harvesting. This thesis is an initial step in the design of textile coils for power transmission comparable to that through a conventional conductive wire. This quite original wireless power transmission method using conductive-yarn resonant coils demonstrated the feasibility for ubiquitous interfaces between wearable devices and energy harvesting technologies based on body movement. When resonant coils made of copper wire and conductive yarn (both having the same diameter and number of coil turns) were compared, it was found that the variation in the signal loss was less than 1 dB. The conductive-yarn resonant coils were placed in the shoes and trouser cuffs of a human subject, and the transmission efficiency was measured using an oscillator and an AC - DC converter. The transmission efficiency varied depending on the movement of the body; however, the average transmission efficiency was 45%, and the maximum change in transmission efficiency was only 6.15% when the subject wearing the coils was running at a speed of 6 km/h. The largest change in body movement occurs in the ankles and trouser cuffs when the subject is walking. Therefore, the changes in the coil shape and alignment conditions were the largest when the coils were located around the ankles and trouser cuffs. In this study, the change in the transmission efficiency was relatively small when the conductive-yarn resonant coils were located at the trouser cuffs. Hence, the proposed technology can be applied to body area networks such as wireless power transmission for smartphones, real-time medical diagnostic devices, and wearable monitoring systems. The design technology used to integrate resonant coils into clothing can be used in the fabrication of a resonant coil or an antenna that can be operated at a higher frequency band such as ultra-high frequency (UHF). Highly convenient data communication or radio-frequency (RF) energy harvesting can be realized

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using such a resonant coil or an antenna, because those devices are integrated into clothing. In addition, wireless power transmission can be used for harvesting and storing energy from human movement, because the resonant frequency of the resonant coils remains unchanged under both flat and bending coil conditions of the human body. The resonant coil made of conductive yarn was fabricated in different sizes depending on the stitch interval, fabric thickness, length of coil, and the increase in coil length, after the conductive yarn was embroidered onto the fabric. However, the resonant frequency of the conductive yarn was obtained from the practical coil length through equations. In the simulation, the number of coil turns can be designed to achieve the resonant frequency under various conditions, as the coils are intended to be operated in the industrial, scientific, and medical (ISM) bands. The practical coil length, however, would be changed owing to the increased coil length after the conductive yarn is embroidered onto the fabric. Therefore, the sending coil with a practical coil length was fabricated, with the number of coil turns being 18. The signal loss was simulated using the simulation model for the arm, flexible PCB, body-worn sensor, and the resonant coils. As in the simulation, the signal loss was measured while the resonant coils were worn on the arm of a human body. The measured signal loss was found to be 2.57 dB and the difference between the measurement and simulation was only 1.75 dB, despite the resistance of the conductive yarn and the eddy-current loss under practical conditions.

In this study, the transmission efficiency was found to be high even though the resonant coils were worn around the arm and not the leg, along with a body-worn sensor. After the resonant coils were worn around the arm, the transmission efficiency was measured using an oscillator and an AC-DC converter. The average transmission efficiency was 52.1% when the subject was moving at various speeds. If the resonance frequency between the transmitting and receiving coils is not matched, there will be a significant change in efficiency based on the movement of the human body. However, if the matching is successful, the wireless power transmission can be performed

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with a change in waveform of about 5% while the human body is moving. Hence, the proposed technology can be applied to wireless charging with textiles, by harvesting and storing energy from body movement; for example, wireless charging for a wireless patch thermometer and wearable sensors. Wireless power transmission using conventional resonant coils provides power at 40 - 75% transmission efficiency, as shown in Table 5.1.

Table 5.1. Performance comparison with existing wireless power transmission technology

	TX / RX Coil size (cm)	Coil structure	Condition	Distance (cm)	Average efficiency (%)
MIT (2007)	50 / 50 (Helical coil)	Copper wire Fixed with styrofoam	No shape change Non-worn No moving	200	40
INTEL (2008)	60 / 30 (Flat type coil)	Copper wire fixed with Plexiglas	No shape change Non-worn No moving	100	75
ETRI (2015)	45 / 35 (Flat type coil)	Copper wire fixed with wireless charging system inside	No shape change Non-worn No moving	100	58
This research	14 / 12 (Helical coil)	Textile-type conductive yarn, Embroidered on nonwoven polyester fabric	Moving Shape change Worn on the ankle and shoe (2 ~ 6 km/h)	1 ~ 2 (Moving)	45
	10x4 / 5x2 (Flat type coil)		Moving Shape change Worn on the arm (2 ~ 6 km/h)	1 ~ 2 (Moving)	52.1

However, the sending and receiving coils with a diameter of 50 cm provide power up to a distance of several meters even when they are not moving. Thus, they have high transmission efficiency; however, users may find it inconvenient to wear coils made of copper wire on their body.

In this study, a wireless power transmission method that involves embedding a conductive material into a fabric was proposed, and the resonant frequency between the sending and receiving coils was designed through equations. The diameters of the helical type transmitting and receiving coils

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located at the ankle and the shoe were 14 cm and 12 cm, respectively, with an average transmission efficiency of 45%. In addition, the dimensions of the plate-type transmitting and receiving coils located on the arm were 10 cm × 4 cm and 5 cm × 2 cm, respectively, with an average transmission efficiency of 52.1%.

Figure 4.8 shows the resonant coils on the ankle, and Figure 4.15 shows the resonant coils on the arm. The change in transmission efficiency is caused by the variation in spacing between the sending and receiving coils during motion. The coils on the ankle are made in helical form. The sending coil is placed on the shoes and the receiving coil is placed on the trouser cuffs. The sending coil is located inside the receiving coil. The coils on the arm are made of flat plates and the sending coil covers the receiving coil, resulting in different efficiency waveforms in the experimental results.

If the resonance frequency between the transmitting and receiving coils is not matched, there will be a significant change in efficiency depending on the movement of the human body. However, if the matching is successful, the wireless power transmission can be performed with a change in waveform of about 5% while the human body is moving.

The resonant coils that are integrated into energy harvesting and storing textiles permit free movement, making the subject feel comfortable. The resonant coil also makes it possible to realize user-friendly energy harvesting, in which energy can be harvested by just wearing clothes that have built-in resonant coils. The modeling technology for the body-worn wireless charging method, which is presented in this study for fabricating resonant coils with the conductive yarn, can be applied for manufacturing custom-made clothing that can maximize the convenience of energy harvesting. This modeling technology can be expanded to harvesting and storing energy based on textiles.

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1. Min Joo Jeong, Jung Hwan Hwang, Sung Weon Kang, and Youn Tae Kim, "Power Transmission through the Human Body using Magnetic Coupling", IEEE International Symposium Antennas and Propagation Society, July 2012

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Abstract

A study on textile-type resonant coils for wireless power transmission in human activity-based energy harvesting

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This thesis presents a wireless power transmission method using magnetic resonant coupling with resonant coils made of conductive yarn that can be integrated into clothing. This conductive yarn consists of silver-plated copper and polyester filaments, and its transmission characteristics were compared with that of copper resonant coils using simulation and measurement tools. The signal loss in the resonant coils was found to be higher than that of the copper coils.

However, the increase in signal-loss variation was less than 1 dB when the transmission distance was less than 6.5 cm. The conductive-yarn resonant coils were placed in the shoes and trouser cuffs of a human subject, and the transmission efficiency was measured, resulting in a maximum transmission efficiency of 50% and average transmission efficiency of 45%, despite the change in the coil shape and alignment conditions due to body movement. An excellent transmission efficiency of over 40% was obtained when the subject was moving at a speed of 6 km/h.

The transmission characteristics of resonant coils made of polyurethane-coated copper and polyester filaments, which were worn on the arm, were evaluated. The change in resonant frequency of the conductive-yarn resonant coils is obtained from the coil length, stitch

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intervals, and fabric thickness using equations.

The measured resonant frequencies of the sending and receiving coils were designed to achieve a resonant frequency of 13.56 MHz when the coils are worn. The resonant coils were worn on the arm of a subject moving at various speeds, and the transmission efficiency was measured, resulting in a maximum transmission efficiency of 55.1% and an average transmission efficiency of 52.1% when the subject was moving at a speed of 6 km/h.

It was also shown that the textile coils could be an integrative solution for providing continuous power supply for the next generation wearable devices without causing any discomfort to the wearer.

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