Towards Standardized Digital Twins for Health, Sport, and Well-being

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Abstract

The digital twin has evolved from the restricted meaning of a replica for a component or system in the industrial process, to a wider definition as a digital replica of any physical entity, including living things. This recent re-definition brings about a powerful concept, bridging the gap between the physical and the digital world for different types of entities, among which human beings are the top of the list. This concept opens new doors for improving the quality of life and well-being for individuals. Indeed, the digital twin concept can be applied to many domains, among which one of the most important domains is the one of health and well-being.

In this thesis, we contribute to the emerging digital twin technology, to enhance well-being of real twins. We leverage the advances in sensing technology and actuation, in cloud computing and data analytics, as well as in data visualization, which are pillars on which the digital twin technology with its new definition is based.

The World Health Organization (WHO) defines health as “a state of complete physical, mental and social well-being”. Possibilities for improvement of well-being are unlimited, nonetheless we show in this thesis how a digital twin system can help establish a better state of well-being in these three areas. The physical, social and mental well-being are all interconnected domains, each affecting the person’s well-being in the other two areas, and we aim at obtaining an improved quality of life in all three of them using a digital twin system.

On a physical health and well-being level, overweight and obesity are globally the fifth leading death factor, and the number of deaths in adults caused by overweight or obesity reaches 2.8 million every year according to WHO. One of the main causes of overweight and obesity is the sedentary life style with non-existent or very little physical activity.

In this thesis, we propose a digital twin framework for health, sport, and well-being. This framework integrates personal health devices, data analytics, and user interaction. It also uses motivational methods to help sedentary individuals get physically active. We specifically tackle the sedentary life style enforced by watching TV for long periods of time daily. We also suggest a social well-being model that encourages the collective production of green human energy, to be donated to poor countries. This system contributes to physical well-being at the same time, and leverages people’s drive for social good to boost their motivation to generate green energy by exercising. This green energy donation model also engages sedentary people in team competitions, while making a better use of the time spent watching TV every day. Besides, other electronics that can also undermine individuals’ well-being is smartphone with its excessive usage. Indeed, studies have shown that it can affect the mental well-being, and we have built an application to help tackle this problem.

Finally, we designed and implemented the different parts of the proposed Digital Twin System based on the ISO/IEEE 11073 Standard, and conducted experiments as a proof of concept for our proposed system. The findings are very promising as our evaluation shows that participants are highly motivated to use this system and had encouraging benefits from it in terms of their well-being.

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Chapter 1. Introduction

1.1. Background

The digital twin concept started in 2002 [1] referring to the digital replica of a physical object. This concept has gained wide adoption in industry due to its high benefits. However, its main uses were and mostly remain today related to the industrial field only.

A new vision of the digital twin was introduced by El Saddik [2] re-defining it as a digital replication of a living or non-living physical entity. By bridging the physical and the virtual worlds, data are transmitted seamlessly, allowing the virtual entity to exist simultaneously with the physical entity. A digital twin facilitates the means to monitor, understand, and optimize the functions of the physical entity and provides continuous feedback to improve quality of life and well-being. A digital twin is hence the convergence of several technologies such as data analytics and artificial intelligence, Haptics and IoT, data visualization techniques, Cybersecurity and Communication networks.

The digital twin as defined in [2] has multiple characteristics. Other than a unique identifier, the digital twin uses sensors and actuators, allowing it to continuously collect data and making it an accurate replica of the real twin at any given time, as well as conveying feedback to the real twin. These sensors and actuators can be in the form of wearables, which use have exploded in recent years. The wearables market is still growing and the data collected by wearables contains valuable health and well-being information that goes mostly unused. With the concept of the digital twin and the structured storage over the cloud of all and any information pertaining to the physical twin, this data will be collected over the history and serve to provide very valuable insight on the health and well-being state of individuals. Data from wearables is also used by a growing number of athletes and can serve to improve the athletes' performance. The instances where this data is used though is still very rare, and the digital twin system has the potential to make its use much more prevalent to serve people's well-being.

1.2. Application Scenario

Let us consider an application scenario. The following case is a very common one: a person wants to become physically fit. In order to achieve that, it is important that the person performs enough physical activity. Therefore, they need to keep track of how much physical exercise they are doing and to know the best personalized exercise plan depending on their preferences. They need to be self-motivated to keep an exercise routine over time. And they need to see visually how this exercise routine is progressing over time, allowing them to see if what they are doing is effective and allowing them to stay motivated by their successes.

We derive several requirements for the digital twin from the described case scenario, which also highlight the significant benefits the digital twin system brings in such a case.

First, the person has to be continuously monitored, in order for his physical activity level to be accurate. Indeed, much of the self-reported data is inaccurate [3], [4], and people are not aware of how long they remain sitting during the day and how little they move physically. The explosion of wearables use came at the right time to facilitate the emergence of the digital twin. Now with high numbers of people wearing all kinds of health monitoring devices, it is time that data from these devices is leveraged to the benefit of people.

While data from wearables is available in high volumes, the fact is that so much of it is lost, because its usability is governed and limited by proprietary data formats from a growing number of manufacturers which shows the necessity for standardization to allow interoperability [2], so data can be transmitted to a coach to help follow up with accurate time spent exercising, not just reported time. And in the case of obesity which is a medical condition, a doctor can access the data as well to monitor his patient.

Visualization of data is of importance in the digital twin system, given the high amount of data collected. The more data collected over time, the harder it is to see any patterns from numbers. However, translating these numbers into well suited graphs will allow care-givers to see patterns that would otherwise remain undetected from seeing just numbers. This provides a source of virtual feedback to follow-up on the real twin’s well-being and/or sport goals.

The digital twin also conveys physical feedback to the real twin through actuators, which play an important role in the digital twin system. Indeed, the strong will such as new year’s resolutions can work for a couple of weeks and then fades, such as many gym memberships that remain unused or treadmills that collect dust in people’s homes. However, actuators in the digital twin system can continuously remind the individual of their exercise time and of their motivation.

In order to provide the right feedback while the person is being monitored, collected data has to be analyzed. This allows personalized actuations for physical activity recommendations and reminders to be developed and provided at the right time. For this, there is a clear need for data analytics and/or artificial intelligence.

Often times, reminders will be ignored such as from smart watches or similar devices. Consequently, a strong motivation such as green energy donation, which also serves the social dimension of well-being as presented later, is needed here. Furthermore, many people complain from lack of time as their primary reason to avoid exercising. Therefore, we make use of the high amount of time spent in front of the TV, especially that the TV is one of the major factors of a sedentary lifestyle.

Cyber-security and privacy are necessary for the Digital Twin system as well. Although these research areas are out of the scope of this thesis, we did take into account related aspects in our system, due to their importance. Notably, all our data transmissions are carried out using a secure connection. Furthermore, all sensitive data that is stored in our database is encrypted.

We thus summarize the requirements described above as follows:

1- Data collection using sensory devices
2- Standardization of data communication
3- Providing real twin feedback through actuators
4- Data visualization to facilitate making sense of data for care-givers
5- Data analytics to detect patterns

1.3. Research Statement

Our objective in this work is to leverage the digital twin concept in the domain of health, sport, as well as well-being. This involves various steps. First of all. It involves tracking the real twin, in order to gather various vital signs related to the real twin's current state of health, well-being, and sport performance. The tracking will allow gathering a significant amount of data, which will need to be analyzed in order to extract useful information pertaining to the real twin's state of health and well-being, and how it is affected by the current real twin's life style. Subsequently, the digital twin can provide the real twin with different types of feedback, recommendations, reminders and notifications in order to positively influence the real twin's behavior and help improve his well-being. Our research statement in this thesis is as follows:

"How can we design and build a digital twin in the health, sport, and well-being domains, for continuous monitoring of individuals' well-being, analyzing the collected data, and then recommending course of action through actuation feedback to improve the real twin's state of well-being."

1.4. Thesis Contributions

The main objective of this work is to design, implement and evaluate a digital twin system for health, sport, and well-being. During this work, the following contributions have been achieved:

1- Design and implementation of an ISO/IEEE 11073 standard (X73) based framework for the digital twin.

2- Design of an algorithm to detect current state of physical activity and motivate the real twin using personalized sensory feedbacks.

3- Design and development of an X73 mobile application to communicate with any X73 standardized device.

4- Design and development of a system to promote social and physical well-being.
5- Design of a probabilistic model to evaluate the performance of the social and physical well-being system.

1.5. Thesis Organization

This Thesis is organized as follows:

- In Chapter 2, we review the background related to the work presented in this thesis;
- In Chapter 3, we explain the proposed ISO/IEEE 11073 standard based digital twin for well-being framework;
- Chapter 4 focuses on the physical well-being aspect of the digital twin;
- Chapter 5 targets the social well-being aspect of the digital twin;
- In Chapter 6, we address the mental well-being aspect of the digital twin system;
- In Chapter 7, we explore the potential of the digital twin system in sport;
- We conclude and discuss areas for future work in Chapter 8.

1.6. Scholastic Output

- Journal articles:

1. Hawazin Faiz Badawi, **Fedwa Laamarti** and Abdulmotaleb El Saddik, "ISO/IEEE 11073 Personal Health Device (X73-PHD) Standards Compliant Systems: A Systematic Literature Review", IEEE Access, vol. 7, 2019 (Impact Factor 3.55).

2. Faisal Arafsha, **Fedwa Laamarti** and Abdulmotaleb El Saddik, “Cyber-Physical System Framework for Measurement and Analysis of Physical Activities”, Electronics, vol. 8, 2019 (Impact Factor 2.11).

3. **Fedwa Laamarti** and Abdulmotaleb El Saddik, “Multimedia for Social Good: Green Energy Donation for Healthier Societies” IEEE Access, vol. 6, 2018 (Impact Factor 3.55).

4. **Fedwa Laamarti**, Mohamad Eid and Abdulmotaleb El Saddik, “An overview of serious games,” Int. J. Comput. Games Technol., vol. 2014, 2014 (150 citations on Google Scholar as of July 29, 2019).
5. **Fedwa Laamarti**, Hawazin Faiz Badawi, Yezhe Ding, Faisal Arafsha, Basim Hafidh and Abdulmotaleb El Saddik “A Standardized Digital Twin Framework for Health, Sport, and Well-being” (submitted).

- Conference Papers:

1. **Fedwa Laamarti**, Faisal Arafsha, Basim Hafidh and Abdulmotaleb El Saddik, “Automated Athlete Haptic Training System for Soccer Sprinting” in Proceedings of the 2019 IEEE International Conference on Multimedia Information Processing and Retrieval (IEEE MIPR), pp. 303–309, March 2019, San Jose, CA.

2. Hawazin Faiz Badawi, **Fedwa Laamarti,** Faisal Arafsha and Abdulmotaleb El Saddik, “Standardizing a shoe insole based on ISO/IEEE 11073 personal health device (X73-PHD) standards”, In: Rocha Á., Ferrás C., Paredes M. (eds) Proceedings of the International Conference on Information Technology &

Systems (ICITS), February 2019. Advances in Intelligent Systems and Computing, vol. 918, pp. 764-778, Springer, Cham.

3. Faisal Arafsha, **Fedwa Laamarti** and Abdulmotaleb El Saddik, "Development of a Wireless CPS for Gait Parameters Measurement and Analysis," 2018 EEE International Instrumentation and Measurement Technology Conference (I2MTC), pp. 1–5, May 2018, Houston, TX.
4. Poppy DesClouds, **Fedwa Laamarti**, Natalie Durand-Bush, Abdulmotaleb El Saddik, "Developing and Testing an Application to Assess the Impact of Smartphone Usage on Well-Being and Performance Outcomes of Student-Athletes", In: Rocha Á., Guarda T. (eds) Proceedings of the International Conference on Information Technology & Systems, (ICITS) January 2018. Advances in Intelligent Systems and Computing, vol. 721, pp. 883-896, Springer, Cham.
5. **Fedwa Laamarti** and Abdulmotaleb El Saddik, "Home automation serving a healthier lifestyle," in Proceedings of the 2017 IEEE International Symposium on Medical Measurements and Applications (MeMeA), May 2017, pp. 39-44, Rochester, MN.
6. Ali Danesh, **Fedwa Laamarti** and Abdulmotaleb El Saddik, "HAVAS: The Haptic Audio Visual Sleep Alarm System", In: Zhou J., Salvendy G. (eds) Proceedings of the International Conference on Human Aspects of IT for the Aged Population, Design for Everyday Life, (ITAP) July 2015. vol. 9194, pp. 247-256, Springer, Cham.

7. Abdulmotaleb El Saddik, Hawazin Faiz Badawi, Roberto Alejandro Martinez Velazquez, **Fedwa Laamarti**, Rogelio Gámez Diaz, Namrata Bagaria, and Juan Sebastian Arteaga-Falconi, “Dtwins: A Digital Twins Ecosystem For Health And Well-Being”, IEEE COMSOC MMTC Communications - Frontiers, March 2019, vol. 14, n. 2, pp. 39-43.

Chapter 2. Background and Related Work

2.1. Digital Twin

The digital twin first started as a concept related to industry and product manufacturing. the digital twin technology potential is such that 62% of companies using internet of things are either in the process of integrating the digital twin technology or have it in their plan, and another 13% of the companies declared that they are already making use of digital twins as reported in a survey conducted by Gartner in August 2018 [5]. That is a total of 75% of the 599 surveyed companies either using or plan to make use of the digital twin technology. One of the benefits is that a certain product has its digital replica that can be manipulated as closely as possible to how the physical product would be manipulated, but at a much more reduced cost. One of the survey findings [6] is that the digital twin is applied to a variety of business objectives.

Another survey on digital twin in industry [7] qualifies this technology as one of the most promising ones for smart manufacturing. Research tackles different aspects in the domain of digital twin. The work in [8] addresses inefficiencies of cost and production in the industrial technology. It suggests the use of a digital twin representing a synchronized replica of manufacturing components and processes, and focuses on gathering tracking data from the past, present and utilizing it for future decision making. The research in [9] describes a digital twin architecture reference model for cyber physical systems, where every physical thing is connected to a cyber thing through sensors. Some other research tackles 3D printing [10] and explains how the digital replica of a 3D printing machines can reduce the cost of printing, by lessening the number of trial and errors, and can make the process also more time effective.

Besides, the interest in digital twins is increasing in both industry and academia [7]. Recently, there is an interest in this concept in the domain of health and well-being, although still very limited. Indeed, a search in Scopus including title, abstract, and keywords for ("digital twin" AND (wellbeing OR well-being)) returns only 1 research paper [2], which discusses the potential of the digital twin concept for human beings and redefines the digital twin as a replica of any living or non-living entity. This redefinition opens doors to extend the benefits of the digital twin concept to human beings. Furthermore, the domain of health, sport, and well-being is one of the domains where this concept can make a positive impact.

Besides, a search in Scopus including title, abstract, and keywords for ("digital twin" AND (health OR healthcare)) returns 45 documents. The same query including title and abstract in Pub Med returns 0 documents. And a search in Pub Med for “digital twin” returns only 4 documents. Many of these publications discuss prognostics and health management of components or machines in the industrial process rather than human health, such as [11], [12], [13] and [14].

However, some of these publications are also related to human healthcare. Some of them are not concerned with the digital twin of a human beings, as they rather propose the digital twin of an emergency unit for example, like the system proposed in [15], or the twin of a hospital like the work proposed in [16], or for chain management of healthcare assisting devices such as the work proposed in [17]. Other research discusses the digital twin in healthcare from the ethical perspective [18], raising points such as the societal potential benefits, but also the possible resulting inequality due to the fact that the technology may not be accessible for all. Very few works related to the health domain, propose digital twins for human beings, such as [19] and [20]. Research in [19] proposes a digital twin for the human head, in order to detect the carotid stenosis severity, while the work in [20] focuses on a framework to monitor elderly patients and help with possible disease diagnosis, or emergency measures that they might need, using digital twin. Both of these two systems are for medical use, and there is a lack in literature for a digital twin system to promote individuals' well-being and sport.

In this thesis, we use the digital twin in its more recent and much broader definition which sees a digital twin as a replica of any living or non-living entity [2]. Some similarities between real and digital twin used in this thesis were extracted from [2]. We use sensors for the digital twin as the humans use their five senses. This is the means used by the digital twin to learn as much information as available about the real twin and his context. This collected data is then stored on the cloud storage which serves as the "memory" of the digital twin. Data processing by means of artificial intelligence algorithms and data analytics, is the equivalent for the digital twin of human intelligence. This allows decision making and transmitting feedback to the real twin. Feedback can take the form of actuation, such as haptic actuation or notifications or manipulation of homes environment to improve the health and well-being of the real twin.

2.2. Smart Homes

Smart homes usages vary from media and entertainment to energy management and security. In the domain of healthcare, smart homes have served in different ways, some of which are for monitoring health condition of individuals, while other research focuses on supporting them in daily life [21]. For example, a smart homes research project described in [22] suggests a health monitoring system for the elderly as well as for individuals returning home after hospitalization. Another research project discussed in [23] proposes an in-home assessment of individuals' functional health using sensory data.

Monitoring physical activity has a wide interest within the research community for different health related reasons. For example, the system developed in [24] wirelessly monitors daily physical activity, the cloud-based system proposed in [25] gathers and analyses biofeedback sensed data and environmental context data in order to provide users with personalized physical activity advice, and the work in [26] aims to assess the risk of physical exercise. Furthermore, multiple research studies have been performed to address health issues related to overweight and obesity, by introducing physical exercise to individuals` lifestyle. A study was described in [27] showing the results of introducing a regular exercise routine to obese women aged on average 59 years. At the end of a twelve weeks study, the women showed signs of health improvements. Other studies involve the use of serious games given their potential to motivate users following specific criteria [28]. A study within this category is concerned with obesity in children [29]. It proposes an exercising game with a foot interface and a heart rate monitor.

Another research using wearable devices was performed in [30] where subjects performed a specific exercise routine. The data collected was used to analyze the impact of exercise on bio-signals, and to assess the compliance to an exercise regimen.

Besides, research has been performed where a virtual health avatar system is developed using data obtained from sensors attached to exercise equipment [31]. Personal health information is then derived from this data and is converted to a standard format based on MPEG-V standard. This information is then reflected on the virtual world avatar in order to help users gain clear understanding of their health condition. The survey in [32] reviews some aspects of the rising interest of the medical and public health communities in 3D virtual worlds, and multiple examples are shown from Second Life.

Advances in technology have potential to bring great benefits to the health domain including both of its fundamental constituents, namely the physiological [33],[34],[35] and psychological health and well-being [36],[37],[38]. Multiple technologies have been proposed such as mobile healthcare [39],[40], healthcare big data [33],[39], and Internet of Things for healthcare and well-being [35], [41]. Multiple health and well-being domains have been studied and solutions suggested include tracking bio signals such as heart rate [42], sleep tracking [43], [44], and stress level monitoring [45]. Advances in smart healthcare services are proposed that transmit tracked health related data directly to the cloud for proper attention and action to be taken by doctors as needed [46] depending on the subject’s health problem. One of the major health problems faced in our modern life is that of overweight and obesity.

2.3. Systems for Overweight and Obesity

Obesity is a global epidemic. There is a high number of studies dedicated to studying and suggesting solutions to the obesity and overweight problem. Monitoring health and physical activity has a wide interest within the research community. For example the work proposed in [47] monitors obese and overweight subjects health using wearable sensors and provides real-time feedback to the doctors. The work in [48] monitors physical activity using smartphone with the aim to estimate the energy expenditure.

Furthermore, some research studies have been performed to address the sedentary lifestyle leading to overweight and obesity by introducing physical exercise to individuals' daily life. A study described in [49] was performed over 4 weeks on individuals who interacted with an online personal activity monitor to increase their regular physical activity. The study found that the wellness score in the intervention group increased as a result, while no changes were observed in the control group. Other studies involve leveraging the potential of exercising games [28]. For example, a mobile app exercise game paired to an exercise bike was tested with a group of college students [50]. The study showed that the game was promising in terms of increasing physical activity level among college students.

However, when dealing with the sedentary lifestyle, it is essential to address the problem of TV watching that drives the global obesity and overweight epidemic. Yet, there are barely any works that take this into consideration when proposing a solution to the physical inactivity. Probably one of the earliest works, which involves a good attempt at tackling this problem, is a device that powers the television set by means of an exercise cycle, which was invented in 1981. Its main purpose was to prevent children from spending too much time watching of what was called “junk” TV [51].

Thus, generating electrical power by cycling is not new. There exists different equipment for using human power to generate green energy, as well as many attempts to harvest the generated energy for different uses.

2.4. Human Green Power

An example in harvesting human energy is Pedalite [52], which is an electrical generator that uses pedaling power with the goal of providing lighting to areas where electricity is scarce or non-existent. This project was designed to use energy generated by both regular bicycles as well as stationary bikes in gyms, in order to charge batteries that can be used later on to power lighting. The idea of producing power by pedaling was also used in the CSI LightCycle, which is a power generator that also uses regular bicycles. Its objective is to provide low cost electricity to people with no access to electric light [53].

In the area of exercise motivation, an interesting initiative using human energy was the installation of an outdoor fitness center in UK [54], which offers the surrounding community with the opportunity to work out for free and generate electricity at the same time. The fitness center produces enough energy needed for its lighting, but the goal is to feed power into the grid and hopefully lower electricity bills. There were efforts towards indoor green gyms as well, such as the Green Microgym in Portland Oregon, where the digital display on the stationary bikes was different than in regular gyms, in that it shows the wattage generated rather than the number of minutes spent exercising.

The idea of green gyms can be found in the US as well, where a New York sports club in Manhattan also makes use of stationary bikes equipped with electricity generators [55]. The generators are connected to the power grid and help the club save on its electricity bills. Similarly, several hundred power generating exercise machines have been embraced by gyms in the United States [55].

In this research, we propose the adoption of green energy producing machines, in order to motivate sedentary people to seek an active lifestyle. To do so, we designed and developed a system, as described in this thesis, that allows individuals to donate the produced green energy to poor countries.

2.5. Convergence of technology and sport

The work contributed in this thesis involves the convergence of technology and sport. It includes the haptic technology and more specifically the haptic feedback. This work contributes to the introduction of technology into the domain of sports, and feeds on the science behind sprinting to provide an automated training system for athletes.

2.5.1. Haptic Feedback

Haptic research involves interest by three different domains: robotics, virtual reality and human computer interface [56], the last of which is the domain that interests the research presented in this thesis.

Haptic feedback has been used to successfully assist users in many different areas. It has for example been used in learning tools such to provide educational applications [57]. It has also been used in health and well-being domains such as sleep monitoring and sleep inertia prevention [44], [43]. Many possibilities have also been explored for haptic feedback in the domain of games for health [28], notably in the area of rehabilitation such as the work presented in [58] where a game for haptic rehabilitation has been conceived and tested that contributes to subjects recovery. A very recent interest in the potential of haptic feedback use in the sports domain [59] has emerged, where the research is still scarce as it is still in its infancy.

2.5.2. Technology in Sports

Technology has been adopted in many health and wellbeing areas and is slowly but steadily making its way into the domain of sports. Many technologies are available to speed up advances in sports, notably in athlete training. Our work uses vibrotactile feedback for the purpose of athlete training assistance. A systematic literature review [60] was conducted with the objective to review systems that use vibrotactile feedback in sports to improve performance skills. This review concluded that vibrotactile feedback has been well established in many medical and non-medical fields, but still needs more research to be done in order to support its use in sports. Indeed, research suggesting systems for athlete training assistance using haptic feedback is still rare, but nonetheless promising.

An example of such systems is the research proposed in [59] which consists of a real time vibrotactile biofeedback system to regulate athlete training intensity. The system uses ECG and force sensors to measure the exercise intensity and calculate the predicted heart rate. Then vibrotactile feedback is used to get the athlete to stay within a desirable exercise intensity zone.

Another interesting research in this domain is the one proposed in [61] which introduces technology to snowboarding. The suggested system provides tactile instructions to snowboarders to assist them with the descent and help improve their skills. The study concluded that tactile instructions are a viable method in sport skill acquisition. A vibrotactile system was also researched in the training of diving athletes [62]. Divers use a wearable with vibrotactile capability that receives signals from a coach monitoring their performance through the system. The study showed better results than video motion analysis. These works are interesting; however, we did not find a research study investigating the use of haptic feedback in soccer and specifically in sprint training for soccer, which is the goal of the case study presented in Chapter 7.

2.5.3. Sprint Training in Soccer

The sport that takes the lead as the most popular sport in the world is soccer. Soccer training, in addition to including soccer specific drills, can also contain sprinting speed development which plays a critical role in soccer play. Research have been performed to study the potential of sprint training in improving athletic performance, such as in [63], where the study results show that soccer training that included repeated sprint drills clearly increased sprinting and vertical jump performance in soccer players more than did the training with the control group that did not include repeated sprint training. The authors also found that the repeated sprint training helped the soccer players in the study effectively improve their physical ability to respond to soccer demands on the body. Furthermore, the sprinting duration has been studied and discussed in [64], where 147 professional soccer players were followed during their play of 10 matches. The study helps distinguish between short sprint duration and long spring duration. The findings showed that during soccer games, 90% of the sprints involved a short sprint lasting about 5 seconds.

2.5.4. Plantar Pressure

It is vital to soccer athletes in any play position to develop a good sprinting speed. Hence, it is important to evaluate the athlete’s sprint technique in order to adjust it and increase the sprint performance. Plantar pressure measurement has been used to evaluate foot performance for different health conditions as well as in sport. Until recently, the tool that has been widely used to measure foot pressure is mats, which are expensive and used mostly in clinical settings. These mats do not allow for sprinting foot pressure study outdoor in the actual field due to portability limitation.

The trend in recent studies is moving towards inserting pressure sensors into shoes or shoe insoles that can then be worn by athletes in the field, which has been used to study foot pressure in sports such as running [65] and soccer [66]. Consequently, we suggest in the work presented in this thesis, the use of a smart shoe insole for the collection of plantar pressure during sprints. Furthermore, we in order to allow the real twins to benefit from the use of the smart insole even further, we suggest using an ISO/IEEE 11073 standard compliant smart insole, to ensure operability and facilitate the use of the collected pressure point data by coaches, physiologists and caregivers in general. The next section presents this standard in more detail.

2.6. ISO/IEEE 11073 Standards-based Health Systems

The explosion of wearable technology and the availability of personal health devices to the general public have a high potential to make healthcare much more efficient in the near future. With this development comes the need for interoperability to allow for more efficient health services and reduce the technological complexity. The ISO/IEEE 11073 standards came to fulfil this need.

2.6.1. ISO/IEEE 11073 Standards

The ISO/IEEE 11073 standards, also called X73 standards, are the result of a collaboration between the International Organization for Standardization (ISO) and IEEE, that came at a time when the need for a standard in this domain has never been higher.

The ISO/IEEE 11073 Personal Health Device standards emerged in 2008 to facilitate communication between personal health devices and managers such as computer system and smartphones, etc. They aim at facilitating health data exchange while providing plug-and-play real time interoperability. X73 standards provides a standardization solution for personal health systems used by both the research community as well as industry.

Research using X73 standardized systems is growing. For example, some research works suggest health-related systems to serve persons at their homes using X73 standard, such as the system in [67] presenting a personal connected health system. Some other systems are mobile and have been designed to monitor people's health parameters remotely such as [68] that provides fall detection.

2.6.2. X73 Standards Personal Health Devices

A variety of X73 compliant devices has been included in research works. An X73 pulse oximeter was used in a mobile Android based system for well-being [69]. The blood pressure monitor was used in an in-home system [70] to monitor some elderly people who are vulnerable to diseases. Other related research works use X73 devices such as the weighing scale [71], the blood glucose meter [72], the body temperature sensor [73], the ECG [74] , the thermometer [75], the shoe insole [76] and other suggested works.

2.6.3. X73 Standards Use in Medical Systems

Some of the systems proposed in literature use X73 personal devices to design medical systems. An example is proposed in [77] where a system was designed to provide patients with medical-care content delivered to their mobile phones. This content is different depending on the patient's profile and their current medical condition. Some research works suggest the use of the X73 standard in cardiovascular diseases. An example of such systems is proposed in [78] which studies issues related to the mobile monitoring of cardiovascular activity and reporting of its malfunction while preserving the mobility of the patients. Another research that focuses on the mobility of the patients and which uses an X73 standardized ECG device is studied in [79]. This work is based on an Android system to allow the patients to monitor their heart condition without having to be at a hospital. An electrocardiogram simulator is used as a source of ECG data to test the system and show that it can display the ECG signal in real time.

The research in [80] proposes a system for the detection of the acute myocardial infarction diseases in order to allow for the necessary early intervention for patients. The device proposed in this research is a wearable device that is not covered by the X73 standard, and so a specification for this device type following the X73 standard has been proposed in this research. The authors suggest the use of the data collected by this device and transmitted to the server for the diagnosis and medical treatment of the acute myocardial infarction disease.

The potential of the use of X73 compliant devices have also been studied in medical conditions other than the cardiovascular diseases. For example, a system that is X73 compliant was proposed in [73] using a body temperature sensor for the use by patients requiring hypothermic therapy. The authors of this research suggest the use of their system as part of the local first aid to monitor the patient’s temperatures until the patient reaches the hospital emergency where caregivers will then have access to the registered data. The authors also suggested the use of their system in sport such as in American football where the players sometimes have lower body temperatures caused by their uniform. The primary focus in the above described systems is on patients with a specific medical condition that needs to be monitored by doctors. However, the main objective of the work in this thesis is to design a system that can help subjects achieve and maintain a healthy condition, while also being available for use by medical doctors as needed.

2.6.4. X73 Standard Adoption in Systems for Well-being

There are more systems targeting patients with medical diagnoses to facilitate monitoring and treatment by doctors and caregivers, and less systems designed for the monitoring of subjects to improve their well-being. Such systems have been researched nonetheless such as the system in [81]. In this work, the authors perform activity monitoring of users, which is done remotely by means of commands sent by a monitoring server. For this, an activity monitor is used on users’ wrist, and can be controlled by the server as needed. Although the paper only presents the system as being for use by medical staff, it is not specific for any health condition and we didn’t find anything in the paper that restricts it from use for well-being as well by healthy individuals.

The research in [82] studies the X73 standard potential through an emulation of an X73 manager communicating with some X73 agents. It discusses the challenges such as moving from fixed systems to mobile with the evolution of X73 standard from point of care for hospital use to personal health devices for particular use by any individual. The research in [82] concludes that this evolution from point of care to personal health device has resulted in an optimization of the end-to-end platform with the advantages of ubiquitous and plug-and-play solutions. The authors of [83] discuss the potential of sharing health data collected from devices following the X73 standard format, between different managers in different locations.

The research in [84] proposes a middleware for mobile health services for collection of health data from personal devices and sending it to a log data node. The authors perform the tests on the proposed middleware using a pulse oximeter communicating with an Android platform.

These described systems are a good step towards the use of technology advances to provide individuals with better options for personal health systems. They ensure the standard adoption but focus mostly on the use of one health device, and they target the collection of health data and its transmission to a server. However, we target in this work to provide individuals and caregivers with a framework that is end-to-end, including the health data collection and transfer but also its analysis and the derivation of vital information to provide the user with feedback. We aim at facilitating the use of any personal health device, while preserving the interoperability whenever a device specification following the X73 standard exists. Indeed, the X73 standards adoption in personal health devices as well as fitness devices is an important part of the work in this thesis. It guarantees interoperability of the collected data about individuals' health, sport, and well-being, and hence ensures the usefulness of this data for caregivers by eliminating hundreds of proprietary data formats caregivers would have to deal with if they want to make use of the personal health data available on the cloud.

Chapter 3. Cloud Digital Twin System Based on X73 Standard

Based on the requirements presented is Chapter 1, we discuss in this chapter the architecture, uses and benefits of the X73 standard-based digital twin system. The World Health Organization (WHO) defines health as “a state of complete physical, mental and social well-being”[85]. Our objective is to design and build a system that helps improve the state of health and well-being of individuals through digitization, processing and analysis of data using the growing computing power of today’s machines.

3.1. DT. Data Sensing

3.1.1. Health and Well-Being Data Collection

The first requirement of our system is the health data collection using sensors. Indeed, researchers have found that self-reported data is not accurate [3], [4]. Additionally, it is tiresome for users to manually enter data in a system through a user interface. This is especially true for a person who wants to improve their health and well-being and is committed to a long term journey and has to enter data manually over a long period of time. Instead, automatic data collection makes the task much easier, much more accurate, and is facilitated now by the explosion of wearables and all kinds of personal health devices.

There is an explosion of wearable use in the past few years. Figure 3.1 shows just some examples of wearables and personal health devices that users are surrounded with every day, such as a smart bedsheet, smart watch, smart insoles etc. Given the increasing use of personal health devices, it becomes critical to adopt a standard to ensure interoperability. Without standards, the data collected by personal devices and containing users' vital signs is unfortunately waisted. The emergence of the ISO/IEEE 11073 (X73) Personal Health Device Standards in 2008 is timely and addresses a pressing need, which is the one of interoperability.

In our architecture shown in Figure 3.2, we use a variety of personal health device types (see Figure 3.5) and we divide them into two categories, in order to achieve the second requirement, which is the standardization of communication of data between devices and server. In the first category, health devices used are X73 compliant and thus able to communicate directly with our X73 communication module. The second category contains the non-compliant devices, as explained later in this chapter.

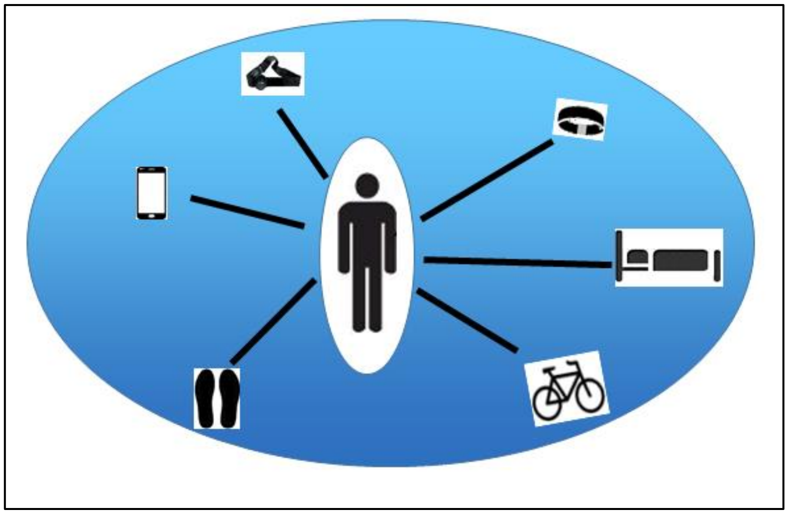


Figure 3.1 Tracking user well-being using personal health devices

3.1.2. Digital Twin Standardization

The goal of standardization in the framework proposed in this thesis is to provide a system that can be used by caregivers in the health and a well-being domain, or by a coach in the sport domain to provide personalized services to athletes. This is without them having to worry about any device’s proprietary communication protocol or data format. The users who will benefit from this service will use personal health devices that are X73 compliant. The bigger problem faced by health and well-being service providers who would like to track their subjects to tailor their service to the subject’s need, is the one of interoperability. Adopting our suggested X73 communication system module would solve this problem.

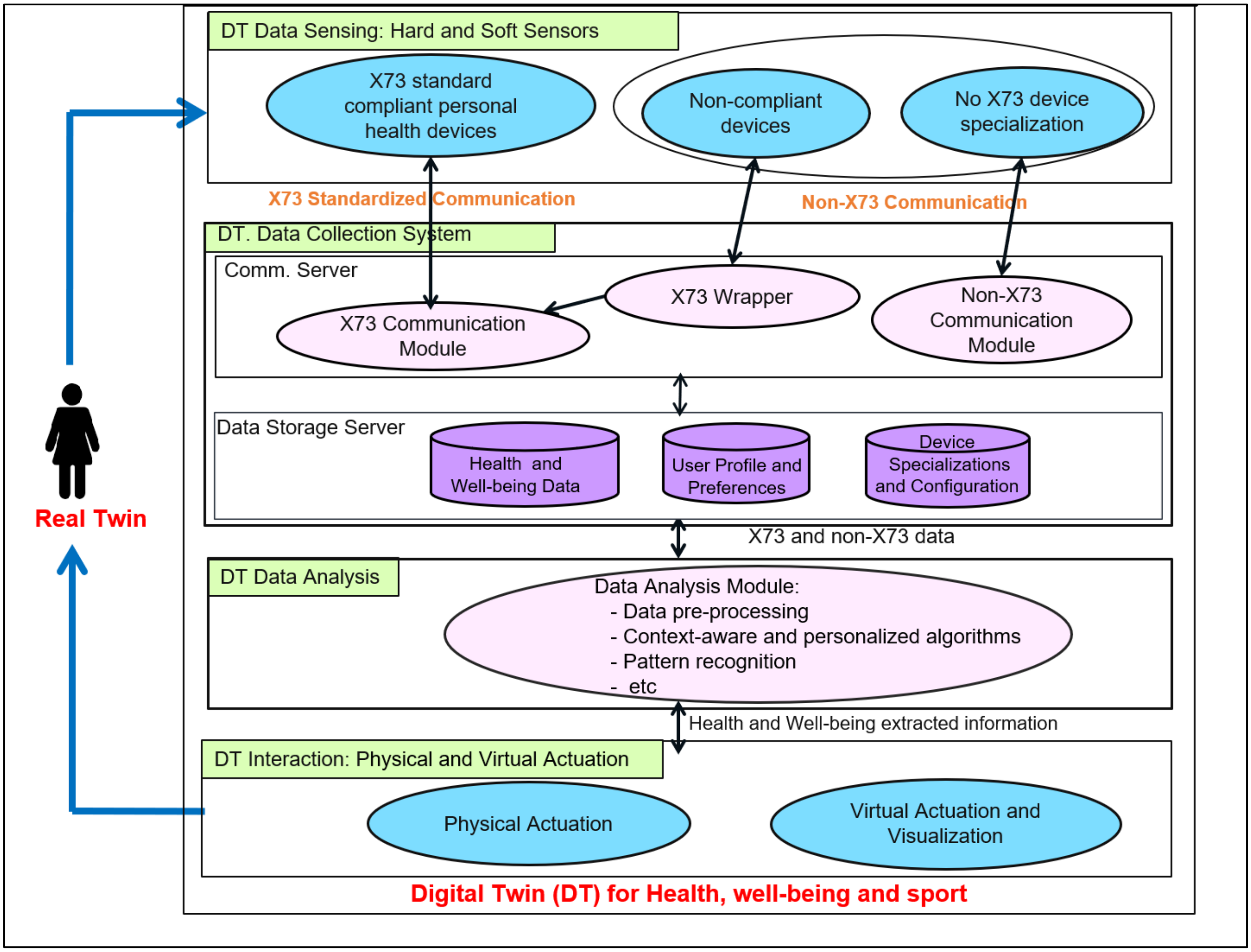


Figure 3.2. Proposed X73-based Digital Twin System Architecture

It is worth noting that only a small number of health devices currently in the market follows the standard, as most wearables are still non-compliant. This is due in part to the recent emergence of the standard. This is also due to the relatively recent explosion of wearables itself, and as such health caregivers are just starting to see the potential in personal health tracking, and to subsequently realize the importance of standard adoption in order to leverage the data from the growing number of wearables. A survey that we conducted on X73 compliant personal health systems [86] shows the interest of the research community in this standard. While health devices standardization is slowly making its way into the world of personal health data collection, there is a need for a solution that can be used promptly, and that includes the existing devices already in use. For this reason, our proposed digital twin framework includes both standardized and non-standardized devices.

3.1.3. Personal Health Devices Categories

The personal health devices are divided here into two categories, as shown in the DT Data Sensing component of the system architecture (Figure 3.2).

1. X73 standard compliant personal health devices: in this first devices category, which are X73 compliant, health devices used are built following the standard and are as such able to communicate with the X73 communication module. This is the server module that follows the standard and uses device specifications designed by the ISO/IEEE workgroup and stored in our server's database. These specifications state for each device type, the information to be exchanged in each of the X73 communication stages.

2. Non-X73 personal health devices: this second category includes all other devices that are not standardized. These devices follow some proprietary manufacturer specification. For this category, we have two sub-categories.

   - Non-compliant devices: this first sub-category contains the device types that do have a specialization defined in the standard, but this specialization was not followed by the manufacturer. For this sub-category, we have designed in our system architecture a module that we call X73 wrapper. This module serves as a gateway between the server and non-standardized devices and is explained later in this chapter.

- No X73 device specialization: this second sub-category includes the existing health devices in use and available in the market which are not standardized nor do they have a standard specialization defined yet. This category has to be taken into account in the digital twin framework, in order to incorporate all device types, while the transition is made slowly towards the standard adoption.

3.1.4. X73 Mobile App

We designed and developed a generic mobile application that communicates with compliant devices in order to collect user data, and send it to the X73 communication model of our system. This means that the mobile device hosting this app is also part of the X73 devices category in Figure 3.2, in the first sub-category which is the X73-compliant personal health devices.

The powerful part about this mobile app is that it can be configured for use with any compliant device, by simply changing its local database to contain the X73 configuration pertaining to that specific device. In our mobile app design, we had a choice between two options. The first is using one mobile app for all compliant devices adopted by a given user. The second is using one app per device. We opted for the second choice because this will keep the app simple, and furthermore, the trend which all users are familiar with, is to have a mobile app for each device.

This mobile application serves as an X73 manager in its communication with a compliant device agent, and serves as an agent in the communication with the X73 communication model of our system. The app collects data from the X73 personal health device, and stores it locally. It uploads the data to the server at the user's request (menu option) or at a set time every day, chosen by the user. When the app sends data to the server, we keep the latest 7 days stored locally for offline user access, and the data that has been sent to the server is flagged to avoid duplicate sending. More data could be kept on the smartphone as configured by the user, we have set the default value to 7 days because of the limited mobile phone storage, and the rest is deleted once the data transfer has been successful.

3.2. DT. Data Collection System

It allows data collection by the cloud server and contains three modules. These are namely the X73 communication module which is the system module that communicates following the X73 standard protocol, and the non-X73 communication module which follows proprietary data formats. The third module is the X73 wrapper, which facilitates the communication between the non-compliant devices that do have a standard device specification available, and the X73 communication module.

3.2.1. X73 communication module

This module is designed and built based on the X73 standard. Following the X73 communication protocol, our communication module acts as what is called a manager. The manager receives requests from personal health devices called agents. First, the X73 manager receives an association request, which it parses to extract the type of the device. This device type allows our manager to use the database to respond with the association response corresponding to the device. The manager also checks the agent identifier and sends within the association response whether it recognizes the identifier and already has this specific agent configuration information in the database. If it does not, the agent has to send its full configuration, containing the device configuration information, that the manager stores in the database, and then sends the accepted configuration response.

The next step in the X73 communication protocol is the operating procedure during which the health data transfer occurs. This procedure contains two stages. In the first one, which follows the configuration stage, the agent waits for the manager to send a request to get the medical device system attributes. The agent responds with a list of its attributes depending on the device. The second stage of the operating procedure is the data transfer. During this stage, the agent transmits its data measurements to the manager, which stores the transmitted data on the cloud. When the data transfer is complete, the agent and the manager exchange disassociation request and response and close the current connection.

3.2.2. X73 Wrapper Module

The wrapper module acts as an intermediary module between non-compliant personal health devices and the standardized communication module. It is depicted in more details in Figure 3.3. Its main role is the data format conversion from proprietary format to X73 standardized format. Which means that this module accommodates non-compliant devices by getting personal health data from them following the proprietary data format. It subsequently communicates as an X73 agent with the X73 communication module, and transfers the collected data to the digital twin cloud database.

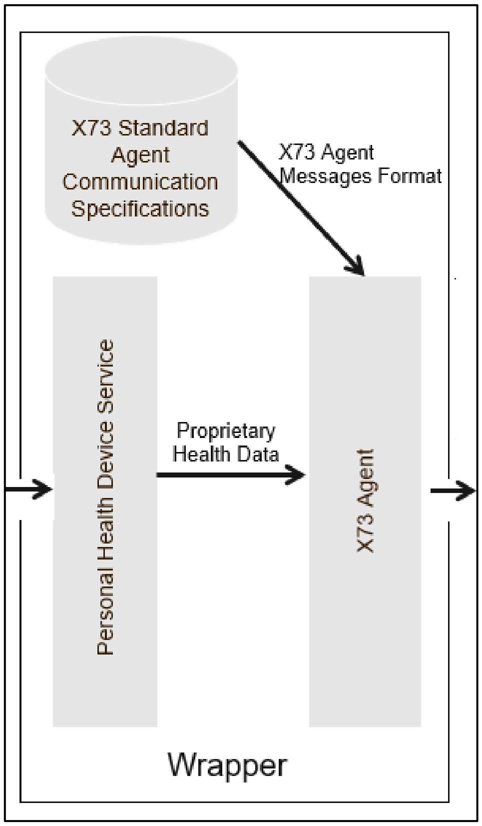


Figure 3.3. X73 Wrapper module

It is worth mentioning that we designed the X73 wrapper as a standalone module that can live on a separate server as needed and transfer the data to the X73 system. This can be especially useful in case of a caregiver who would only host the standardized system and not worry about any proprietary devices communication, which is very understandable. The wrapper module would then be hosted and maintained by a third party offering this service, and allowing inclusion of data from as many devices as possible in order for it to be useful to the individual wearing those devices.

The wrapper module can transfer data from a proprietary device as long as there exists a device specialization defined for this type of device. ISO/IEEE personal health device standard currently has 15 devices that are included in the standard and have an active device specialization. However, many other devices do not have a specialization defined yet, even though they are widely used in the market. There are research papers that propose device specializations for some these devices such as smart phone camera, Wii Balance Board and the shoe insole, and the list of standardized devices is growing.

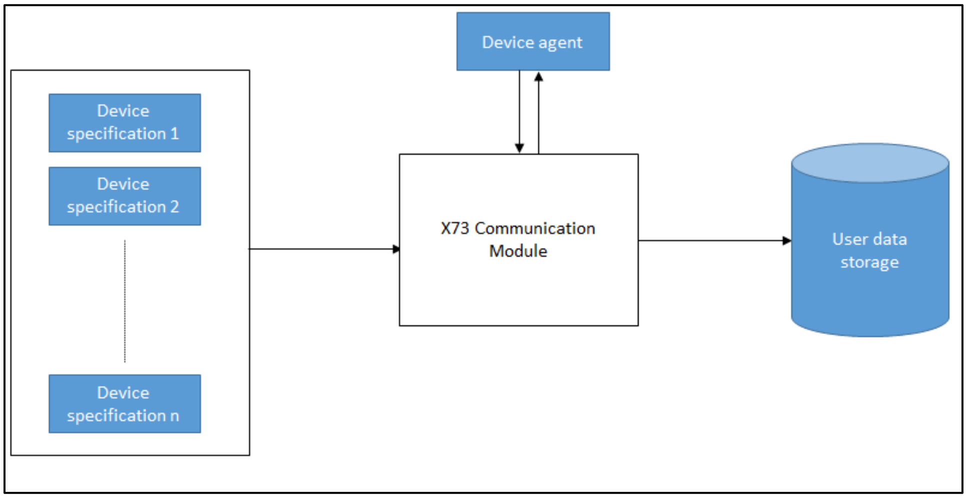


Figure 3.4. Configurable X73 Communication Module

3.2.3. Configurability of the X73 System

We designed the X73 communication module to be configurable. To achieve this goal, we first designed the system to follow the main specification of the X73 personal health devices 11073-20601 that all device specializations are based on. Then, we made the specifications, which are particular to each device type, configurable in our system database. The communication module reads those specifications from our database and excludes any device specific configuration from the code. Subsequently, we included all the available specializations into our server database, as shown in Figure 3.4. With this design, any X73 compliant device is able to communicate with our system, as it is required to follow one of these specializations. It can thus transmit data in a plug and play manner, without any human intervention.

We did not find such configurability in any other X73 system, as the systems we surveyed [86] were designed for specific device types, and any additional device types would necessitate changes in the design/code or addition of extra modules to handle them. This configurability is important, because any new device type standardized by the ISO/IEEE working group can be smoothly incorporated into our system without further implementation. Indeed, the new device specialization will be added to the database, and personal health devices that follow this specification will be recognized seamlessly by our system.

The importance of this configurability is even more so because of the continuous improvement and changes brought by the ISO/IEEE working group to the device specializations, as the standards are fairly recent. So in our case, the changes can be brought to the database and we do not need constant changes in the code, which is convenient for caregivers who choose to make use of our system.

3.3. DT. Data Analysis

The digital twin objective is to understand the real twin’s state of health and well-being which can be achieved through data collection, data storage and then data analysis taking into account the history and the current state of well-being in order to detect patterns. This can be achieved through algorithms and artificial intelligence, and take into account the external context of the real twin as much as possible. After that, depending on the real twin personalized objectives, and depending the real twin context, the role of the digital twin is to provide context-aware feedback and recommendations through real and virtual actuators. The range of possibilities that can be achieved using this concept is very wide and the potential of improving individuals' well-being is high. This is especially true with explosion of wearables and the vast variety of health parameters they can track and make available for data analysis, the increasing processing power of today's machines, and the advances in artificial intelligence. Thus, what can be achieved through the digital twin system is very diverse and open to the creativity of researchers and caregivers. We present in the following chapters of this thesis, case studies design and implementation as proof of concept of how the digital twin system can help improve the state of well-being of the real twin.

3.4. DT. Interaction: Physical and Virtual Actuation

3.4.1. Providing user feedback through actuators

Physical as well as virtual actuation are used in our suggested framework to provide feedback to the real twin, based on digital twin examination to collected data over time. The goal from this is to make the real twin aware of his own state of well-being, and to positively influence his behavior and motivate him to take action in order to improve his state of well-being. Different motivational methods can be used such as leveraging people inclination for social good in order to motivate them to physically exercise while donating green energy to the poor.

With the advances in technology, a wide variety of physical actuators exist today and have the potential to make a positive impact in the real twin's life if used creatively. For example, haptic feedback can assist in sport training as shown in Chapter 7, ambient intelligent environments can be leveraged to set the stage for an active life-style as demonstrated in 0, and virtual feedback like persuasive notifications can improve social well-being as shown in Chapter 5.

3.4.2. Data visualization

Data visualization is part of the virtual feedback conveyed to the real twin and/or to caregivers, but not necessarily in real time. It is important as it allows caregivers to make sense of the data and facilitate detecting patterns that can go unnoticed from the data itself. Examples are graphs that show how the real twin has progressed over time, such as in terms of physical exercise. Another example is heatmap visualization showing foot pressure that allows a health care provider or a sport physiologist to see possible imbalances in the athlete's posture.

Another purpose of the data visualization that we make use of in this thesis is the user motivation. We provide graphs to show the user see his progress over time, for example in terms of physical exercise, in order to keep them motivated by past successes to perform more. We also use comparison graphs that show how the user performed in comparison to the average performance. As examples in this thesis, we use comparison graphs for individuals in terms of energy donations and for coaches and athletes to show them athlete performance. Since this compares to the average then the others users' privacy is not compromised.

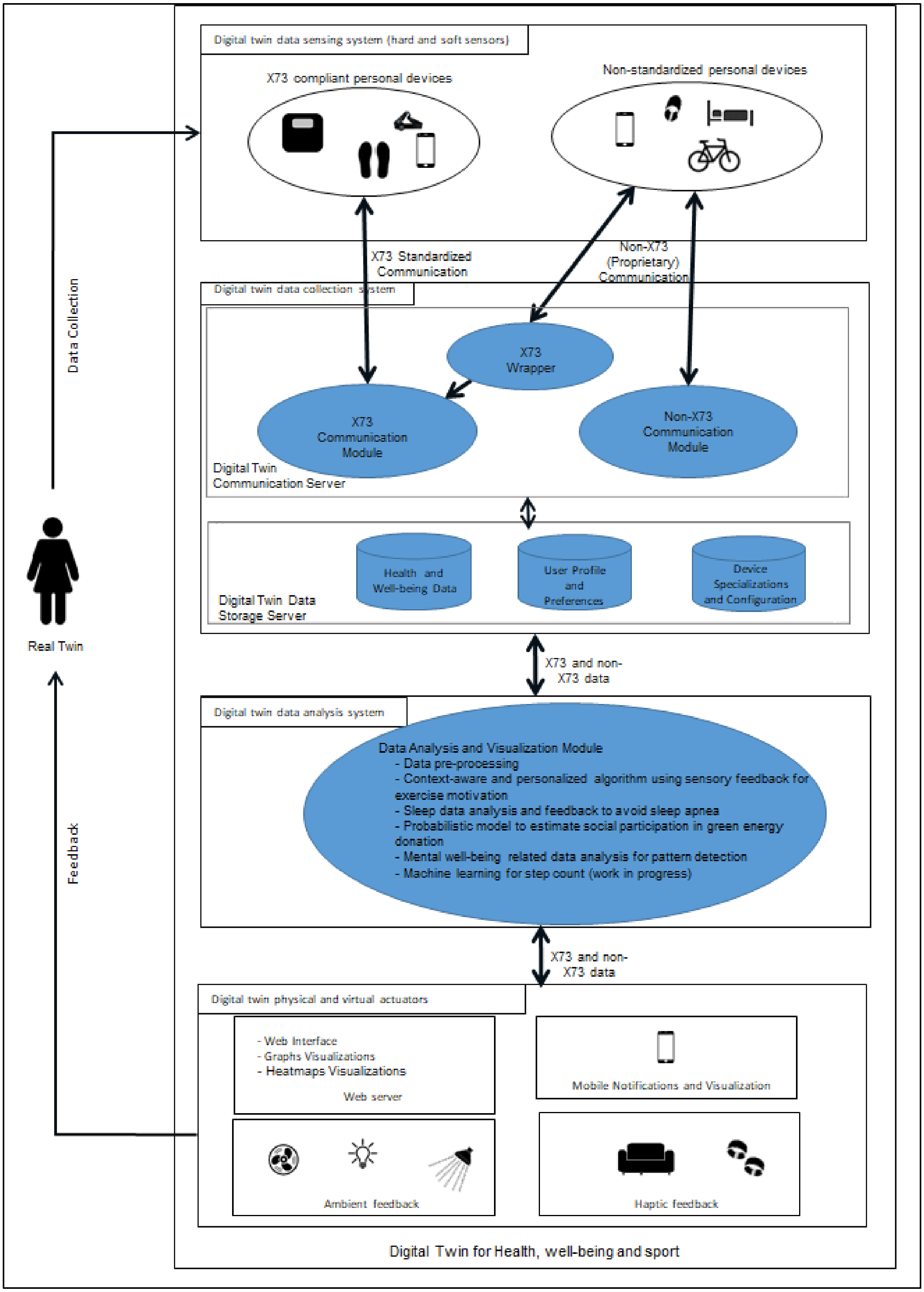


Figure 3.5. Summary of X73 Digital Twin for Well-being Designed and Implemented in this Thesis

3.5. Conclusion

We have presented the digital twin framework that allows the integration of both standardized and non-standardized devices to allow collection of as much data as possible on the real twin in order to serve him better. As explained earlier, the definition of health by WHO involves three aspects, namely physical, social and mental well-being. In addition, we are very interested in the inclusion of the sport and exploration of how the concept of digital twin can assist and potentially improve athlete training. In the rest of this thesis and as a proof of potential of our framework, we will present an application of the digital twin system for each aspect which are physical, social and mental well-being and sport. This will allow the reader to get a sense of how the digital twin can improve health and well-being of the real twin through data collection, storage, analysis, and user feedback. We will explain the design and implementation of each aspect of the system as well as the conducted experiments and their results.

Chapter 4. Digital Twin for Physical Well-being

In this chapter, we focus on the physical well-being profile of the digital twin. Of particular interest is the physical activity level as detailed in the following section. The loop starts by the real twin for whom we collect data on the physical activity level. This data is sent to the server which stores it and runs data analysis on it taking into account the real twin preferences and data history. This is important in order to have a personalized recommendation for the real twin. We then use the extracted information to provide feedback and improve the physical well-being of the real twin.

4.1. Importance of Increasing the Physical Activity Level

The increase of obesity and overweight is alarming, and has major human and financial detrimental consequences. The problem of obesity and overweight is caused mainly by an increase in physical inactivity, for which one of the main reasons is the long hours spent every day in front of the TV. The system proposed in this chapter targets individuals who are overweight or subjects for whom doctors have recommended a minimum physical activity. We use the digital twin system feedback in this work in order to control home actuators as a motivation for individuals to transform exercise intention into exercise activity. To evaluate our system, we conducted an experiment with 31 subjects, and the results are promising as they show that our system was successful at motivating subjects to perform physical exercise while watching TV.

4.2. Challenging Aspect of Healthy Lifestyle

When aiming to promote a healthy lifestyle among the overweight and obese, one of the hardest challenges faced is introducing a regular exercise routine for a minimum duration. If we take a look at the statistics about the disproportionate amount of time that people spend watching TV every day, it becomes clear that dealing with the TV can certainly make a difference in increasing the physical activity pattern of many people, children and adults alike. In fact, Americans spend an average of over 4 hours a day watching TV, which is the equivalent of 9 years of uninterrupted TV watching over a 65-year life-span [87]. In this chapter, we suggest a motivational system during the time a subject spends in front of the TV in order to encourage viewers to get physically active. One of the important aspects of the present work is to build a health-related framework that promotes physical exercise and that is standard-based.

4.3. Use of Standards

We described in the previous chapter that we adopt the use of standards in order to make our digital twin system independent of manufacturer's proprietary products. While X73 standard has been adopted in this thesis to collect data from personal health devices, it does not cover rendering devices which are out of the scope of this standard. Hence, we make use of the MPEG-V standard [88] for other sensory devices and actuators used in this system, for the purpose of interoperability. The MPEG-V standard requirements document also includes sections concerned with health [88]. MPEG-V media context and control (published in ISO/IEC 23005) [88] is a standard for allowing interoperability between virtual worlds or between virtual worlds and the real world. For example, the authors in

[31] use the MPEG-V standard to control virtual world health avatars by real world devices. In their study, they explore how a health avatar can be controlled by users in the real world while performing physical exercise. It is to be noted that although we have used MPEG-V as a standard to communicate with rendering devices, we have opted not to include it as a required standard in the digital twin framework proposed in this thesis. Indeed, a standard to communicate with personal health devices is required, because the valuable health data will be useless, unless a standard is made use of, in this case the X73 standard. However, the use of a standard to communicate with rendering devices, even though very beneficial, remains optional, as no health data is lost as a result of leaving it out.

One of the uses of MPEG-V Media context and control (ISO/IEC 23005) is to standardize sensory effects production during movies presentation in order to enhance the viewer's experience in a 4D environment [89]. In this work we propose the usage of sensory effects while watching TV as a motivation to subjects to perform physical activity while still watching their favorite program. In the remaining of this chapter, we explain this application in reference to the framework architecture presented in Chapter 3, then we explain our approach in using the digital twin concept explained earlier to help improve the real twin's physical well-being. We subsequently discuss the results of our experiment.

4.4. Proposed Solution

Our proposed solution uses sensory effects which are triggered when the user profile shows that their exercising level is below the threshold defined in the system. These sensory effects include couch vibrations, both at a low intensity and a higher intensity, light level control, lowering the air conditioner's temperature, airflow generation and water spraying. Their intensity is increased gradually during the process. Finally, the system goes on to automatically combine sensory feedback as long as the user is still not performing physical exercise.

The proposed system architecture is illustrated in Figure 3.2. We show the architecture with an emphasis on the case study of physical well-being in Figure 4.1. The input data is collected from a stationary bicycle and a weighing scale. And the system output is the user feedback by means of the rendering system consisting of an Arduino board that is connected to a set of hardware rendering devices which produce the actuations' effects. These rendering devices include vibration motors that produce the couch vibrations, a light dimmer to control the light level, a fan to generate airflow and a water sprayer to render the water spray effect.

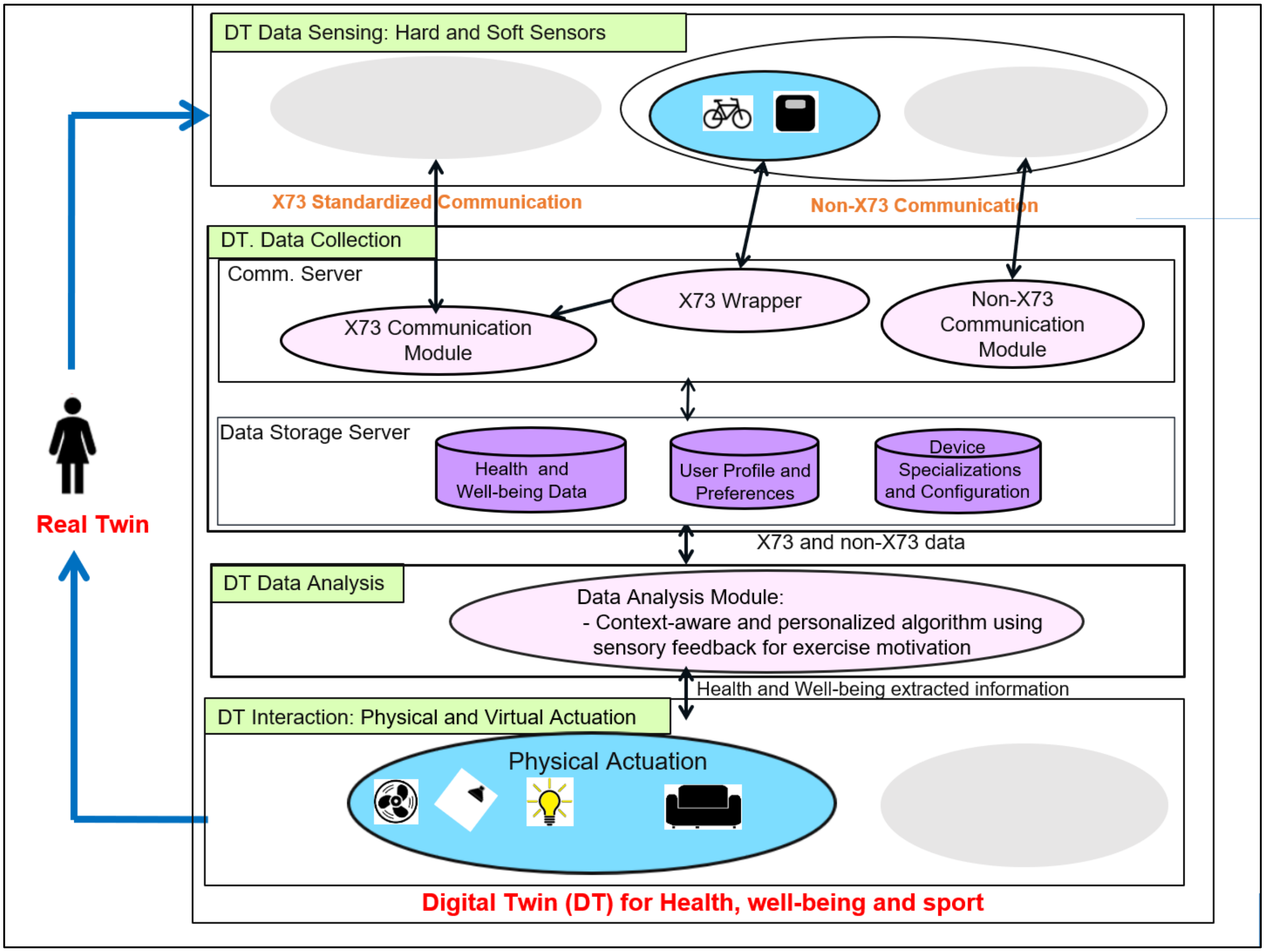


Figure 4.1. Case Study for Physical Well-being System Architecture (adapted from Figure 3.2 and hence components non-relevant to this case study are faded out)

Given that X73 standard covers input devices and does not address rendering devices, we adopt the standard MPEG-V for interoperability purposes as different rendering devices use different proprietary formats. The MPEG-V standard has seven parts, out of which three parts are relevant to our work. These three parts are Control Information (Part 2) which provides device capability description of the actuators, Sensory Information (Part 3) which standardizes the description of sensory effects, and the Data Formats for Interaction Devices (Part 5), which defines the format of the device commands.

Besides, an adaptation engine is used here as we describe in the next section, in order to bridge the gap between the real and virtual world, and is not within the scope of MPEG-V standardization. This adaptation engine is a virtual to real engine, and is designed to adapt the commands sent to the real world actuators.

4.5. Method Description

In this chapter, we propose using the digital twin framework to contribute to the real twin's physical well-being by increasing the physical activity level, and overcoming overweight and obesity. To achieve this, we make use of the real twin's profile and history stored on the cloud, and we control actuators as means of feedback and as a motivator to increase the physical activity level.

The actuators when activated produce sensory effects, which are the following: couch vibrations with increasing intensity, airflow effect generated by a fan, light level control (increased/decreased intensity), water spraying, and air conditioning (decreasing the temperature).

There are two aspects of interaction between the real twin and his digital twin. First in the real to virtual interaction, personal health devices are used to monitor the exercise level of the subject. Here a stationary bicycle is used to collect the RPM (revolutions per minute) and hence monitor the speed of the biking exercise. The exercise history is stored on the system database. On the other hand, the digital twin interacts with the real twin by controlling the real world. Indeed, the motivation system engine checks the exercise level history. If the real twin's exercise level is found to be below the minimal threshold set in the system, the motivation system engine triggers the process of stimulating sensory effects. Sensory effects commands are then sent by the virtual to real adaptation engine to the different devices. These devices include vibration motors, a light dimmer, a water spray, a fan. The resulting sensory effects produced are stopped as soon as the real twin starts exercising as shown by the RPM received from the stationary bicycle.

4.5.1. Collection of Exercise Data

Different types of personal devices can be used to transfer the real twin information (physical activity level) to the digital twin, such as exercise equipment accompanied by sensors to capture the activity level. We use a stationary bicycle in our system to demonstrate this concept's feasibility, but multiple options are available to users. The X73 wrapper receives the RPM data received from the bicycle and converts it into a standardized format in order to preserve the system's interoperability.

Furthermore, for the data carrying the RPM, the angular velocity is used. This is because RPM is not accepted as an international standard since it is not a standard unit, and so we need to convert it to angular velocity. The unit used for measuring angular velocity is radians per second and it is commonly represented by the symbol omega ω. The formula for the angular velocity is given by equation (4.1) as follows:

$$\omega = \frac{d\theta}{dt} \qquad (4.1)$$

Where: $d\theta$ is change in angular displacement

dt is the change in time.

In our case, we have a spinning bicycle wheel which is similar to a rotational disc. If we suppose that its speed is 1 rpm, then it completes 1 full revolution or rotation in 60 s.

The change in the angular displacement is $d\theta = 2\,\pi$ radians

The change in time is $dt = 60$ seconds

So 1 rpm = $2\pi / 60$

The angular velocity ω is then given by equation (4.2)

$$\omega = \frac{d\theta}{dt} = \frac{2\pi}{60} \times \text{rpm} \ \ (\text{rad/s}) \qquad (4.2)$$

4.5.2. DT. Feedback to Promote Physical Activity using Actuators

When the pressure sensors on the couch indicate that a person is sitting in front of the TV, the exercise history is automatically checked. The process of sensory effects is subsequently launched if the history shows that the real twin has not performed enough exercising. The sensory effects commands are then sent to the rendering devices.

1) Sensory Information (MPEG-V Part 3)

The sensory effects are described following the MPEG-V standard Part 3 Sensory Information. This part of the standard defines the Sensory Effects Description Language (SEDL), an XML-based language that allows defining the sensory effects metadata (SEM). The sensory effects themselves are then defined using the Sensory Effect Vocabulary (SEV) which allows applications to describe a set of sensory effects as required. The sensory effects that are used in our framework are produced with an intensity and duration that increase gradually. The intensity and duration of the effects are defined using the standard, as shown in the excerpt below. For the light sensory effect, levels are defined from 1 to 7 and each level corresponds to a range of intensity defined by the standard. For example, level i $(1 \leq i \leq 7)$ corresponds to the intensity interval range shown in equation (4.3):

$$]\,(\mathrm{i}-1)\times \mathrm{offset}\ ..\,\mathrm{i}\ \times \mathrm{offset}\,] \qquad (4.3)$$

Where offset is defined as:

$$\mathrm{offset} = \frac{\text{maximum intensity}}{\text{number of levels}}$$

Exerpt 4.1 shows a vibration effect description. The intensity of 10 as shown in the exerpt is measured in Hz, within a range of 0 to 20 Hz. The duration parameter is the number of seconds that the effect will last. Then the number of seconds of the effect fade-out is 2 seconds.

```
        <Effect      xsi:type="sev:VibrationType"      intensity-value="10.0"
intensity-range="0.0 20.0" duration="5" fade="2" si:pts="0"/>
```

Exerpt 4.1. Example of a vibration effect description

2) Device Commands (MPEG-V Part 5)

The virtual to real adaptation module maps the sensory effect elements as described above, to device commands, which allows controlling the real world rendering devices according to the virtual world context. The Device Command Vocabulary (DCV) of MPEG-V allows sending specific commands to the real world actuators. For instance, to generate an airflow effect, the device command type “WindType” is used.

```
        <iidl:InteractionInfo>
           <iidl:DeviceCommandList>
        <iidl:DeviceCommand  xsi:type="dcv:WindType"   id="airflow01"
deviceIdRef="airflow001" activate="true">
```

Exerpt 4.2. Example of airflow generation command.

Exerpt 4.2 shows an example of a device command generating airflow as defined in the standard. The example shows a command to generate an airflow effect using the device referred to as “airflow001” which is a fan. The device command activates the fan when required by the system.

3) Control information (MPEG-V Part 2)

Control information defined in MPEG-V Part 2 carries, among others, data about the sensory devices capabilities. The Device Commands can be further improved by adjusting it according to the sensory devices capabilities, which are covered in the Control Information (MPEG-V Part 2). The devices capabilities are provided to the virtual to real adaptation engine, so that they can be combined with the devices commands information and result in a more effective interaction with the real world devices. Control Information is described using the Control Information Description Language (CIDL) which is an XML-based language defined in Part 2 of the standard. The CIDL language allows the instantiation of the Device Capability Description Vocabulary (DCDV), which is used for the description of the real world sensory devices capabilities. For example, when a light effect is to be generated in our system, the description of the light capabilities will be provided as illustrated in Exerpt 4.3. In this example, the identifier of the light is “light_01”. This light has 7 levels and can display a white color. It also has a maximum intensity of 100 as specified in this command.

```
     <cidl:SensoryDeviceCapability
List>

<cidl:SensoryDeviceCapability
xsi:type="dcdv:LightCapabilityTyp
e" id="light_01 "
unit="urn:mpeg:mpeg-v:01-CI-
UnitTypeCS-NS:lux"
maxIntensity="100"
numOfLightLevels="7"
```

Exerpt 4.3. Example of a light capability

4.6. Sensory Feedbacks Experiment and Results

We first need to define priorities of what effects are more motivating than others. This way, the most motivating effects could be left last, to have a gradual persuasive system. The best way to determine the order of priority of effects can be achieved by conducting an experiment. The users will rate what effects were the most motivating/annoying, and they would most want to avoid. This experiment also allows us to evaluate the degree of effectiveness of the sensory effects and their influence on subjects' motivation to exercise while watching TV.

4.6.1. Experimental Setup

A total of 31 participants of different educational backgrounds (aged between 20 and 49, where 16 are males and 15 are females) participated in our experiment. Prior to the experiment, 26 participants reported that they either do not exercise at all or exercise less than 30 minutes per day; and 5 subjects exercise between 30 minutes and 1 hour. All the subjects started the experiment at a time when they did not perform half an hour or more of physical exercise during that day. The subjects were invited to have a seat and to watch their preferred TV program. They were advised that some sensory feedbacks (without specifying which ones) would take place. The subjects were also told that it was their choice to remain seated or to exercise on the stationary bicycle, and that if they started exercising, the sensory feedbacks would be stopped.

Every participant started by sitting on the couch and by watching a program of his/her interest on the TV for a little while. Then the sensory effects were launched and the user's response to each effect was registered. Every subject experienced each of the sensory feedbacks for 30 seconds, in order to determine if the feedback had any influence on the user, before the next feedback was launched. The air conditioning sensory effect was not part of this experiment as we conducted the experiment in the lab and we had no direct control over the central air conditioning device.

4.6.2. Experiment Results

A summary of the findings is shown in Figure 4.2. The sensory feedbacks had different impacts on participants. Indeed, some were influenced by a given feedback more than by another feedback. For example, a user would perform exercise as a result of the airflow, while another subject is more influenced by the light sensory effect.

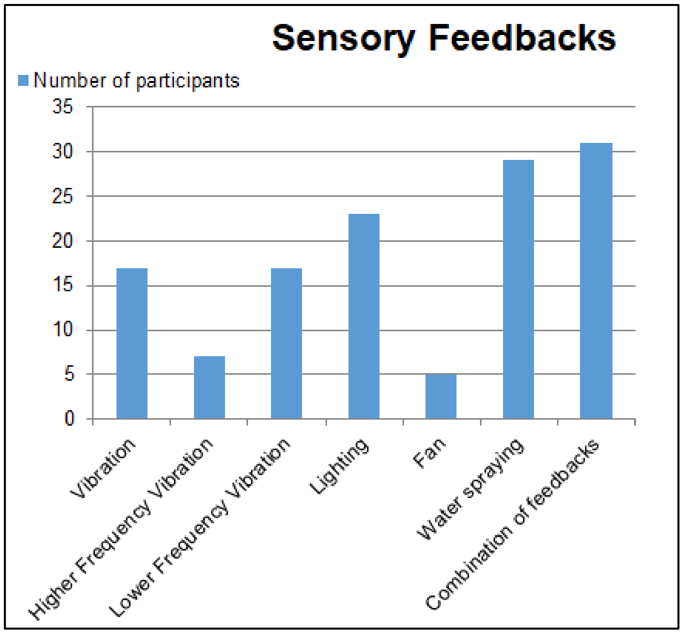


Figure 4.2. Effect of the sensory feedbacks

The vibration from the actuators on the couch's seat had a positive response from 17 participants, where the most responses came from the lower frequency vibrations. In total, the vibrations motivated 54% of the subjects to perform the bike exercise. The lighting effect, including dimming and brightening the light had a positive effect on 23 participants. That is a percentage of 74% of users who were incited to exercise as a result of this effect. The air flow generated from the fan was the least effective of the feedbacks and had an effect on 5 participants, or 16% of the users. On the other hand, the water spray was the most effective of the feedbacks with an effect on 28 participants, which represent 92.32% of the subjects who were incited to exercise on the bike as a result of this feedback. Lastly, the combination of feedbacks had an effect on all of the participants who performed exercise as a result.

Among all the participants only one subject did not exercise as the result of single feedback. This subject preferred multiple feedbacks simultaneously as a result of the activation of multiple actuators and then performed the required exercise. All 31 subjects responded well to the system as a result of one or more sensory feedbacks, which means all of them responded with the targeted result of leaving the couch and performing exercise while watching TV. We conclude that adopting such a system reveals promising in getting users physically active.

Another conclusion that we drew from this experiment has to do with the order of feedbacks. Since we aim for having a system that is gradual in terms of inciting users to perform exercise, we plan to order the launching of sensory effects starting by the one that has the least impact in terms of number the users, which is the air flow effect generated by the fan. This will be followed by the higher frequency vibration, and then the lower frequency vibration, etc. This order is concluded from the number of users influenced by each effect. But the effect of the feedbacks differed from one user to another during the experiment. Thus, the system will still have to offer customizability to users following their preferences.

4.6.3. Post Experiment Participants Evaluation

Finally, the participants were handed a questionnaire to evaluate the system. 21 of them (67.74%) declared that they would like to adopt the system to make sure they do exercise the recommended 30 minutes every day. Some of the comments on the questionnaires stated “I usually forget about exercising, this system reminds me to exercise” or “I am looking for new ways to motivate me exercise”. On the other hand, 10 participants said they would not like to adopt this system, some of the reasons being “I don't watch TV that much, it will help me if we apply the system to my work.”

4.6.4. Study Limitations

This study presents noteworthy results. Some limitations exist though, such as the fact that this study was conducted in a laboratory-controlled environment. Thus, it would be interesting to study and report on how the users would react to the system in an actual home environment. Other potential improvements include a randomization of the sensory feedbacks before conducting the experiment with each participant, in order to study if the order of the sensory feedbacks has any effect on the obtained results.

Chapter 5. Digital Twin for Social Well-being

According to the World Health Organization, social well-being is a fundamental aspect of health, along with physical and mental well-being. A study defining the wellness determinants defines wellness in accordance with the World Health Organization definition [85] as follows: “Wellness refers to diverse and interconnected dimensions of physical, mental, and social well-being that extend beyond the traditional definition of health. It includes choices and activities aimed at achieving physical vitality, mental alacrity, **social satisfaction, a sense of accomplishment, and personal fulfillment**.”[90]. Social well-being is based on five elements [91], one of which is the **social contribution “the belief that one is a vital member of society, with something of value to give to the world**”[91]. In this chapter, we will address the social contribution aspect of social well-being. We present an application of the proposed framework for social well-being, to show how the digital twin system can improve social contribution through data collection, user feedback, and data visualization.

Since all aspects of well-being are inter-connected, it is not possible to completely separate between those aspects and draw a clear distinction line. It is also a well-known fact that the different aspects of health and well-being affect one another. Therefore, in this chapter we present the social profile of the digital twin that serves social contribution and healthier physical aspect of the real twin, which is to help decrease obesity and overweight. Indeed, obesity trends are alarming. The number of obese adults and children has doubled since 1980 [92]. Obesity has also almost tripled since 1975 [93]. Besides, obesity and overweight are major risk factors for heart disease, stroke, and diabetes [93]. The statistics of overweight children are also alarming: in 2016, 41 million children under five years of age were overweight or obese [93]. The sedentary life style with virtually no physical activity is a major cause of overweight and obesity.

In this chapter, we suggest a model of the digital twin for social well-being that allows individuals to make a difference in the life of the less fortunate by pedaling and donating the generated green energy. In return this model helps the overweight and obese, as well as people leading a sedentary lifestyle in general, as the health risks of sedentary life are not limited to people with excessive weight. The proposed model is a cloud-based and harnesses people's motivation for social good to encourage them to engage in physical activity to contribute green energy while watching TV. Lack of time being the excuse of many people who don't perform physical activity, this is not an issue here as we are making use of the time already spent watching TV. The suggested system allows individuals to generate green energy for the benefit of countries in need. Other motivational aspects of this system are also explained in later sections, such as allowing collaboration between system users and displaying personalized and persuasive notifications during exercising sessions.

We designed and developed an application of the digital twin system that leverages people's motivation for social good and promotes physical activity. Furthermore, the system application we propose at the same time allows people to contribute to a greener planet, while motivating them to be healthier by encouraging them to perform the recommended physical activity. Our proposal includes a multi-level motivational system that uses human green power generation by making use of power producing exercising machines, and benefits from the inclination of people to work for a social cause, in order to attract masses to burn calories by pedaling. It is a cloud-based exercising system, allowing for competitiveness and collaboration, that can be plugged into social media, and that collects green energy for donation to poor countries. In the rest of this section we will define in more detail the different aspects of the suggested system.

Figure 5.1 illustrates the social well-being case study of the digital twin system. In our proposed digital twin system, every real twin has a profile on the cloud with a history of exercise and green energy donations. Here we used a stationary bike as our sensor for physical activity data collection. But again, users who adopt this system are free to pick their exercising machine of choice such as a treadmill or an elliptical that generates power.

Before starting the exercise session, the user signs in to his account online on our system. As shown in Figure 5.1, the exercising machine is monitored by our system. Whenever the input indicates that the bike is now in use, ie the RPM (revolutions per minute) is different than zero, our application parses the data received from the bike to extract the watts, the RPM and the gear. The application then starts sending the exercise data to the cloud-based server of the digital twin system, indicating the user id so that the data can be assigned to that real twin's profile and stored in the database. The system displays to the real twin on the screen the speed and the estimated calories consumption as well as the duration of exercise. The largest display on the screen though, is that of the increasing green energy generated for the country of choice, to keep up the users' interest and motivation.

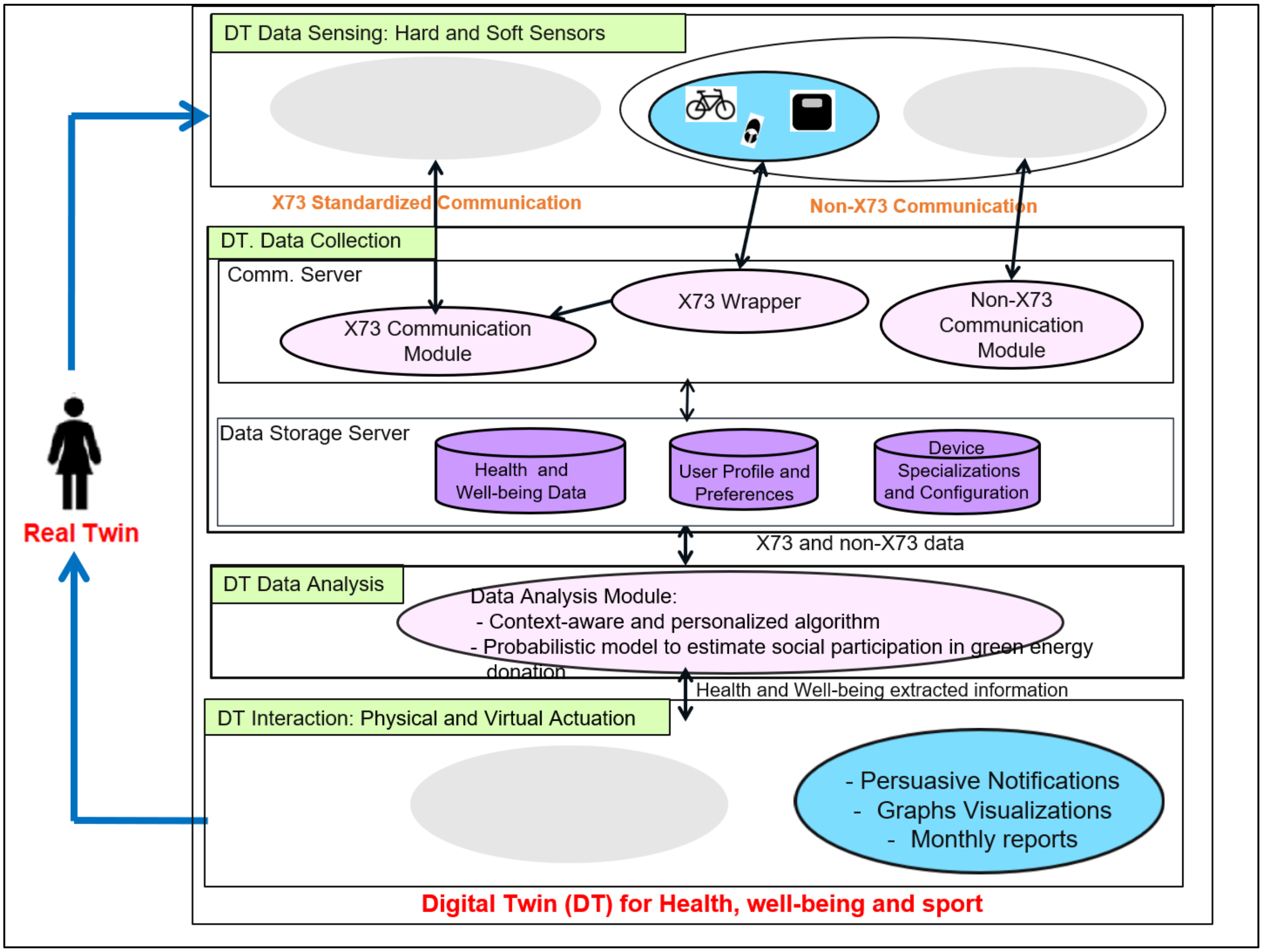


Figure 5.1. Case Study for Social Well-being System Architecture (adapted from Figure 3.2 and hence components non-relevant to this case study are faded out)

The system has a competition as well as collaboration aspects integrated. Indeed, the users can collaborate as teams depending on their country of choice for donations. They also compete against other teams donating to different countries to see which team donates more. Every month, the users can change the country they donate to, and so a new team is automatically formed.

The user can view different charts showing his exercise history subsequently to an exercise session, or just as his convenience. These include the estimated calories burned, the duration of exercise and the green energy he generated over time. The system also allows the user to visualize the energy generated for each country, as shown in Figure 5.3 in the results section.

5.1. Green Energy Generation

Our main goal from the proposed system is to use green energy generation and donation as a motivating factor to encourage the obese and overweight, as well as people with a sedentary lifestyle as a prevention measure, to exercise and burn fat.

A lot of time is being spent every day watching TV as mentioned earlier, so for people who are not willing to put in extra time for exercising, this system will allow them to use the time already spent in TV watching by pedaling on a stationary bike instead of sitting on the couch. The pedaling process will then allow green energy production and donation to poor countries, where many people can either collaborate or compete as we will explain later in this section.

It is sometimes argued that generating energy using equipment manufactured for this purpose is not energy efficient, because it consumes energy to make the equipment in the first place. But many individuals will buy treadmills anyway, that sit in the basement and collect dust. Additionally, and more importantly, here the purpose is to contribute a solution to a big problem which is obesity on which tremendous amounts of money are being spent each year. So, such a motivational system can actually save money, and has the potential to also save human lives. Indeed, 400 000 deaths are registered every year in the United States, and $117 billion are spent on obesity related health issues every year[92].

5.2. Social Good

In this digital twin for social well-being application, we provide the user with regular virtual feedback. Indeed, the suggested system aims at motivating people to exercise for a social cause, which is donating free and green energy to poor countries. Thus, during the process of exercising, we display personalized notifications to keep the person focused on how much energy they have accumulated for donations. We also get our system users more involved by giving them full choice of which country they would like to donate to, which makes them more committed to their goal.

A question that is relevant here is how much energy is generated by cycling? A person can generate anywhere between 100 and 400 watt by pedaling for an hour. An athlete cyclist can produce even more than 400 watts [55]. Although if we consider only one person pedaling, this amount of energy is not considerable. But the group effect that we're aiming to get here, is the factor that will make a difference. Furthermore, when we consider the high energy consumption in richer countries, we find that the energy generated is only a small portion of the consumption. However, this is not relevant anymore when we consider poor countries. Indeed, in this system we want to motivate people to get physically active in order to donate the energy produced to developing countries with very low electric consumption. For example, if 100 watt-hour makes very little difference in countries that are highly energy consumers, it is a considerable amount of energy for countries with far lower energy consumption rates.

To make this point factual, let's consider the world's most electric power consuming countries, shown in Table 5.1, as well as the world's least electric power consuming countries, as shown in Table 5.2. The data in both tables is a sample of data collected by the

World Bank Group for the year 2014 [94]. Now, if we compare consumption in developed countries such as Iceland at 53 832 KWh per capita, or Canada with 15 545 KWh per capita, to that of countries such as Haiti at 38 KWh or Sudan at 39 KWh per capita per year, it becomes very clear that an amount of generated electricity that is insignificant in developed countries with their high consumption rates, is substantial when donating it to countries in need.

Table 5.1
Electricity consumption in the World's most consuming countries extracted from worldbank.org [94]

Country Name	Electric power consumption for the year of 2014 (KWH PER CAPITA)
Iceland	53 832
Norway	22 999
Bahrain	19 592
Canada	15 545
Qatar	15 309

On average, a person in Norway consumes in one day more energy than what a person in Niger consumes in a year. And with an average consumption of about 100 Watts per day in Haiti, (and as low as 66 Watt per day in 2010 when it was struck by an earthquake), a person there could surely benefit from energy generated during an exercise session donated by a person with access to the Green Energy Donation System recommended in this thesis. Many other countries have very low electricity consumption, some of which are shown in Table 5.2, and can greatly benefit from energy donations.

It is to be noted that the electricity consumption numbers shown in Table 5.2, and extracted from the World Bank statistics, are based on the consumption per capita. However, not everyone in the listed countries has access to electricity. Therefore, individuals with electricity access have a relatively higher consumption, on average, than shown in this table. On the other hand, since this table displays consumption averages, the disparity between economic classes hints us that electricity consumption in poor people is lower than the numbers shown in this table. Consequently, the numbers in Table 5.2 are for illustrative purposes only, to give the reader a good idea on the potential of green energy generation in helping individuals in countries in need.

Table 5.2

Electricity consumption in the world's least consuming countries extracted from worldbank.org [94]

Country Name	Electric power consumption for the year of 2014 (KWH PER CAPITA)
Tanzania	99
Ethiopia	69
Niger	51
South Sudan	39
Haiti	38

5.3. Cloud Based System

The model that we are suggesting in this thesis is cloud-based. As such, the information about the user’s exercise history and green energy generated are uploaded to the cloud and stored in the database in order to allow for performance visualizations and encouragements. Indeed, the information about the exercise history will be used to display encouragements to the user if he has been getting the right amount of exercise, or motivating messages to do so. Another use of the exercise history is for the accumulation of the amount of donated energy for the online collaboration or competition between users over our system as explained below, which will allow determining which participant or team of participants has accumulated the largest green energy donation.

5.4. Online Collaboration

Gamification is an important concept which is being used more and more recently. It is based on the inclusion of the play aspect into tasks that would otherwise be daunting or unpleasurable. One element of gamification that can make a significant difference is the aspect of collaboration or competitiveness. Indeed, in a survey on serious games that we found a study reporting an experiment which results show that the same game that is made social by being played in collaboration or competition with other people becomes much more appealing.

Following this finding, we included into our system an aspect of collaboration of team members as well as competitiveness between those teams by accumulating watts generated, as a kind of points system. Donations are made competitive between teams in order to propel energy generation and increase physical activity.

Our system facilitates teams formation online based on the country chosen by each participant. Teams accumulate watts following the exercise history of their team members, and the country that is in the lead in terms of accumulated donation is displayed online on the system, to encourage rivalry between teams. Finally, graphs that show exercise history, calories burned and how much green energy was donated to a country, are available on the system for the users. This visual aspect is important and can help make users aware of how well they have been improving over time, in terms of physical activity while watching TV.

5.5. Persuasive Notifications

Persuasive notifications are personalized messages of short duration played by the system when the real twin is pedaling while watching TV. Their purpose is to encourage individuals to exercise for a longer duration, following the information collected about their exercise performance in the system. Indeed, when the real twin signs in to the system, it will automatically load their profile. This loads the country that the real twin chose to make donation to, as well as how much energy they have generated so far. And since the system is aware of the duration that the person has been biking, a notification is displayed periodically, depending on the duration of exercise performed so far, in order to encourage the individual to hit the next milestone in donation. An example is letting the person know that exercising 10 more minutes will allow completing donation for a full day to the country of choice.

Since the data concerning every person’s exercise history and donation history is stored into the database, this allows tailoring the persuasive notifications to each person’s history and profile. Additionally, since these are displayed on a separate screen that is connected to the system, they do not interfere with the TV watching. The notifications show how much the real twin has contributed to the energy donation and how much is still needed to compete with donations to other countries. For example, if the country of choice is Haiti, then to encourage a person to exercise more, information will be displayed to remind the person that in Haiti, the average individual consumes in average about 100wh per day. Or if the country of choice is Bolivia, the notification displayed is then similar to the following: “If you exercise for 7 more minutes you will reach enough energy for one person in Bolivia for the day”.

5.6. Experiment and Results

5.6.1. Experiment Objectives

The objective of the system evaluation is twofold:

-- First, checking the individuals’ willingness to use this system, with the motivation to donate green energy.

-- Second, evaluating the duration and intensity they actually exercise while using this system, and evaluating whether it’s promising in terms of health benefits.

We are targeting individuals with a sedentary lifestyle, so if the system motivates them to exercise for about 10 to 15 minutes at first, this is a reasonable expectation and it is promising that they can work their way up from there. Also, for physical exercise to have good health benefits, it has to be intense enough to fall within the moderate-intensity interval, which we will define later in this section.

5.6.2. Phase 1: short range experiment

1) Procedure

We thus conducted an experiment to evaluate the Green Energy Donation proposed system. 11 subjects, 6 males and 5 females, aged between 25 and 59 years old participated in this experiment.

Prior to the experiment a questionnaire was completed by all subjects, to determine their daily physical exercising habits. The majority declared they do not perform physical exercise. Only one participant reported he gets the recommended 150 minutes of exercise per week [93]. And none of the users exercises during working hours, such as going for a little walk or just pacing down the hallway to move their body, to which one of the participants answered “of course not”.

All subjects had a mini information session, where facts about the difference in electric consumption from the World Bank as shown in Table 5.1 and Table 5.2 were shared with them. We also briefly went through some health risks of a sedentary lifestyle as well as physical activity recommendations from WHO [93].

2) Experiment and Results

The subjects then were directed to create a user account on the system and proceed to select a country of their choice that they would like to donate green energy to. We informed every participant that the exercise duration is open and will depend on how much energy they would like to donate to their country of choice.

All of them stepped on the weighing scale device connected to our system to collect their weight and conducted the experiment wearing a Fitbit device, so we can monitor the heart rate. They were asked to pick their favorite TV program which they would like to watch before starting the exercise session on the stationary bike. The duration, the pedaling speed, and the heart rate were all monitored during every exercise session.

The countries donated to were varied, some users selected the country based on the least consuming, or the closest to their back-home country, or chose purposefully the one that was not chosen by others, which balanced to countries donations nicely. The fact that our system allows users to see how much energy was collected for every country so far proved beneficial.

The participants had a free choice as to how long they would exercise, and they were informed that there was no minimum exercise duration. We also let them know that they can watch TV as they usually do but this time they will be pedaling with an extra screen in front of them allowing them to monitor the exercise session. The duration of exercise ended up being between 20 and 32 minutes, with an average of 25 minutes.

In the green energy donation application of the digital twin system, we found that the target being the wattage generated and not merely the duration of exercise was very valuable, as this kept the participants pedaling at a good pace in order to generate more energy. As a result, the heart rate was raised as explained below, as recommended by the American Heart Association.

Indeed, the heart rate (HR) was monitored using a Fitbit device. Figure 5.2 charts the HR for one of our participants during the experiment. This participant exercised for about 21 minutes, from minute 19:13 up to 19:34. We included in Figure 5.2 a few minutes prior and then post experiment for more clarity. We noted that the HR was raised during the exercise sessions, which indicates the experiment resulted in beneficial exercising. Indeed, according to the American Heart Association, a heart rate of 50 to 70 percent of the person’s maximum heart rate is recommended for moderate-intensity exercise, and 70 to 85 percent of the maximum heart rate indicates vigorous exercise intensity. We calculated the maximum HR for our participants and most of them had a period that falls within the vigorous exercise category. For example, for the participant in Figure 5.2, the HR peaked to 133 about halfway through the exercising session. His maximum HR being 172 (constant 220 minus the age), he was thus within the vigorous-intensity interval at about 78% of the maximum HR. This is a very good achievement for a person who does not perform daily physical activity.

All of the experiment subjects were in at the recommended moderate-intensity exercise during a portion of their session, and 75% subjects also reached the vigorous-intensity interval heart rate. This exceeded our expectations, as our goal was only to get our participants to exercise within the moderate intensity zone as recommended by the American Heart Association.

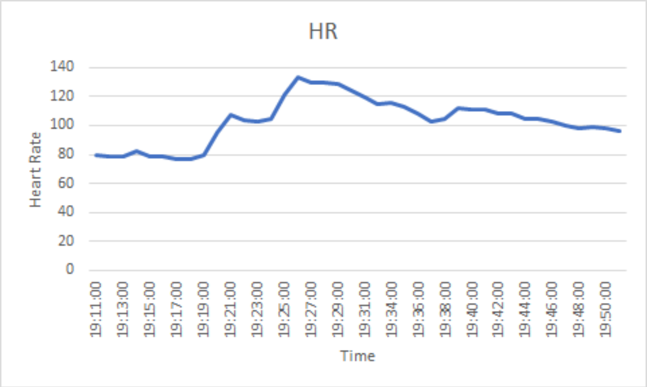


Figure 5.2 Heart Rate for a Participant in the Experiment

The five countries with the lowest consumption in the world, (see Table 5.2) were available in the system for the subjects to choose from. The green energy generated during the experiment week is distributed over countries, as chosen by the participants, as shown in Figure 5.3.

We found that the participants were very competitive as well. Almost all of the users were asking how much the other participants have generated, “so I can generate more” they would say. On the other hand, some of the subjects had a different motivation. They would just view in the system the daily consumption of their chosen country, and would work towards the target wattage, in order to donate enough energy to one person in the chosen country for one day. They reported that the system giving them visibility about the energy consumption of the poor countries is beneficial and allows them to pedal for the right duration. We noted that more often than not, if a participant completed the exercise duration they had planned for, but their TV program was not finished yet, that they actually preferred to keep pedaling to generate more energy while watching. Many participants commented that they felt their time watching TV was put into good use.

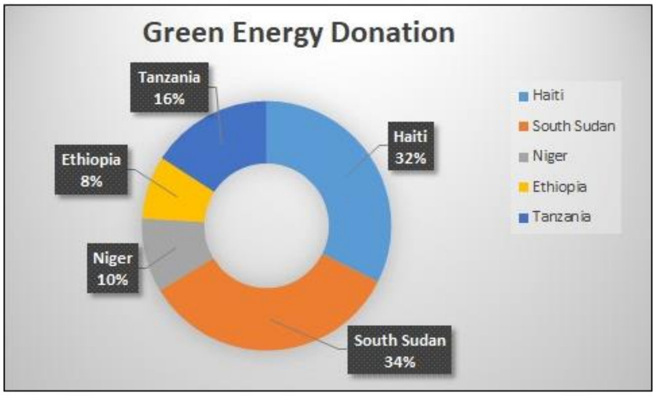


Figure 5.3. Green Energy Donation to Countries

Moreover, we found that a lot of the time, the participants would forget about the duration of exercise and would focus more on the wattage generated and **make**

comments on reaching their goal for donation. We also noticed that they stop thinking about the exercising aspect for a stretch of time and will just be absorbed watching TV while pedaling, which kept them going for a longer time.

The post study questionnaire was handed to the participants to evaluate the Green Energy Donation system. On a scale from 1 to 10, 10 being the most effective, they evaluated the system between 8 and 10, and the average evaluation was 8.6. All subjects were positive that they would adopt this system to ensure that they get the recommended physical activity, and that they would like to have such a system set up at home.

The participants affirmed that they would use the system for a duration of about 30 minutes per day, and two of them said they would use it for up to 45 minutes.

In this post evaluation, the participants also reported that it's a win-win system where they are motivated to exercise **for a useful and good reason**. Some said it is an excellent idea, combining entertainment (watching TV) with energy donation, especially that it is green energy. Some subjects said that **they are motivated to help others with essential needs** such as electricity, while maintaining their own health and fitness. It was also noted that with this system, no extra time is needed to exercise, because time is already being spent watching TV. Many participants reported that they ended up exercising more than they expected, as the majority of them lead a sedentary lifestyle.

Table 5.3
Exercise duration, first without the system then with the system

	Exercise Without the System						
	Day 1	Day 2	Day 3	Day 4	Day 5	Mean	Stand Dev
Participant 1	8	8	5	8	8	7.4	1.34
Participant 2	5	10	5	5	2	5.4	2.88
Participant 3	5	10	10	5	10	8	2.74
	Exercise With the System						
	Day 1	Day 2	Day 3	Day 4	Day 5	Mean	Stand Dev
Participant 1	21	30	20	23	32	25.2	5.45
Participant 2	25	20	24	21	20	22	2.35
Participant 3	30	23	27	35	30	29	4.42

5.6.3. Phase 2: longer range experiment

1) Procedure

We conducted a second experiment, with the objective of evaluating the potential long-term benefits of the system. We asked three subjects, 2 males and 1 female, to participate in a two week-long experiment. During the first week, they were just asked to report their daily exercise duration without having access to the system. Subsequently, during the second week, they were asked to use the system to exercise for 5 days, taking two days off. The duration however was still left open to the subjects' discretion as was the case during the first experiment. This is in order to approximate, as accurately as possible, the exercise duration during the system's free daily life use, should it be adopted by individuals.

2) Experiment and Results

All three participants conducted the second experiment wearing the Fitbit device, allowing us to continue to monitor the heart rate. They first chose their favorite TV program before starting each exercise session on the stationary bike. The duration, the pedaling speed, and the heart rate were monitored during the daily exercise sessions.

We found that the objective being the energy generation and donation and not just the duration of exercise, the participants were making real effort during the exercise sessions in order to keep generating more watts, as opposed to just spending a certain number of recommended minutes exercising. As a result, all of the exercise sessions ended up in a lot of sweat, and the HR was consistently in the moderate intensity range, and was reaching the vigorous exercise intensity inconsistently, as in bursts of increase of pedaling pace. Something that we noticed very frequently was the uplifting effect of the sessions. Indeed, there was a positive change in mood in the experiment subjects after using the Green Energy Donation system, which can be attributed to a good exercise session, or to the feeling of generating energy for a good cause, or both.

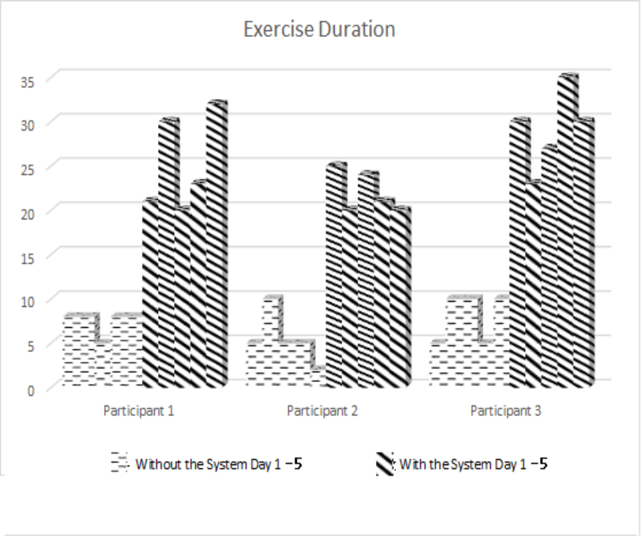


Figure 5.4. Results comparing the exercise duration with and without the system

Table 5.3 summarizes the second experiment exercise duration results. In the first week, the five days of reported exercise are nowhere near the recommended 150 minutes per week. Most of our participants also reported that the exercise they performed was casual walking, which raises the question of whether this would qualify as moderate exercise as the American Heart Association recommends. Besides, it is of importance here to note that some studies show that moderate exercise for 15 to 20 minutes a day reduces some health risks of sedentary lifestyle [95]. But When we look at the exercise duration as was reported during the first week, it is well below the 15-20 minutes range of physical activity. To the contrary, most of the exercise sessions performed during the second week while making use of the system are equal to or higher than the 15 to 20 minutes threshold, as illustrated in Figure 5.4.

Furthermore, the American Heart Association recommends 150 minutes per week of moderate activity or 75 minutes per week of vigorous exercise, or a combination of moderate and vigorous exercise. And the heart rate results obtained show that our participants are either in the moderate or vigorous exercise zone, which proves that the exercise performed using the system fulfills the recommended duration and intensity.

5.7. Performance Analysis

5.7.1. Estimation of Exercise duration

In this section, we analyze the performance of our system based on the empirical data that we gathered during the experiment and the data collected in the pre-experiment questionnaire, where participants reported their exercise habits. We use probabilistic modeling to estimate the exercise duration of a person who is making use of this system. In what follows, the assumption is made that the exercise duration of an individual for a given exercise session, follows a Gaussian (normal) distribution.

Thus, in the following, we assume two gaussian distributions:

-- the physical exercise duration without the use of our system, noted $N(\mu, \sigma)$, and

-- the physical exercise duration with the help of our system, noted $N'(\mu', \sigma')$

Where the parameters used (mean and standard deviation) are defined as follows.

-- μ represents the average exercise duration without the system,

-- σ is the standard deviation of the Gaussian distribution model without the system,

-- μ' represents the average exercise duration with the system, and

-- σ' is the standard deviation of the Gaussian distribution model with the system.

The two distributions are given by equations (5.1) and (5.2):

$$\boldsymbol{N}(\mu, \boldsymbol{\sigma})(\boldsymbol{x}) = \frac{\mathbf{1}}{\boldsymbol{\sigma}\sqrt{\mathbf{2}\boldsymbol{\pi}}} \boldsymbol{e}^{-(\boldsymbol{x}-\mu)^{\mathbf{2}}/(\mathbf{2}\,\boldsymbol{\sigma}^{\mathbf{2}})} \qquad (5.1)$$

$$\boldsymbol{N}'(\mu', \boldsymbol{\sigma}')(\boldsymbol{x}) = \frac{\mathbf{1}}{\boldsymbol{\sigma}'\sqrt{\mathbf{2}\boldsymbol{\pi}}} \boldsymbol{e}^{-(\boldsymbol{x}-\mu')^{\mathbf{2}}/(\mathbf{2}\,\boldsymbol{\sigma}'^{\mathbf{2}})} \qquad (5.2)$$

Table 5.4.
Probability of exercise duration assumed to follow Gaussian distribution for the three participants.

		$P_{N(\mu,\sigma)}(a \leq X \leq b) =$ $P_{N(\mu,\sigma)}(X \geq a) - P_{N(\mu,\sigma)}(X \geq b)$					
		a=0, b=5	a=5, b=10	a=10, b=15	a=15, b=20	a=20, b=25	a=25, b=30
Participant 1	No System μ=7.4	0.037	0.937	0.026	0	0	0
	With System	0	0.002	0.028	0.139	0.315	0.325
Participant 2	No System μ=5.4	0.414	0.500	0.055	0.001	0	0
	With System	0	0	0.001	0.195	0.703	0.100
Participant 3	No System μ=8	0.135	0.631	0.227	0.005	0	0
	With System	0	0	0.001	0.020	0.162	0.407

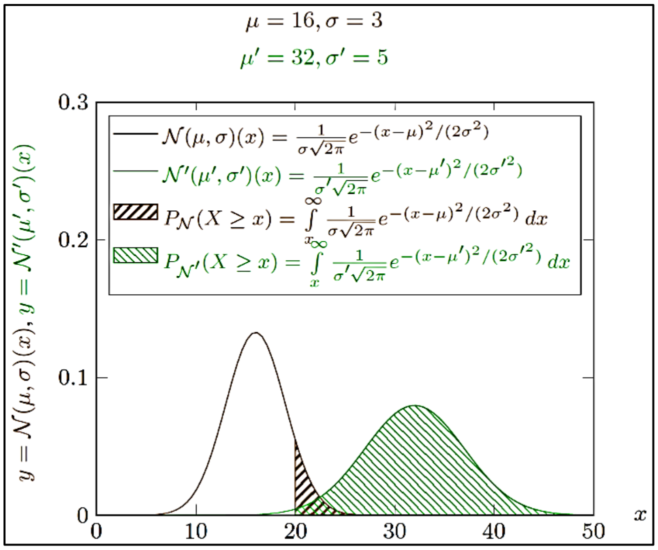


Figure 5.5. Normal distribution illustration of the exercise duration for a given participant in the system.

The Gaussian distributions plotted in Figure 5.5 show the pattern for exercise durations, first without the system $N(\mu,\sigma)(x)$, and then with the system $N'(\mu',\sigma')(x)$.

X is a random variable representing the duration in minutes a given participant spends exercising. The shaded areas under the bell curves represent the probability that the exercise duration *X* is higher than a certain value *x* without the green energy system $\mathbf{P_N}(\boldsymbol{X} \geq \boldsymbol{x})$ given by equation (5.3), and with use of the system $\boldsymbol{P_{N'}}(\boldsymbol{X} \geq \boldsymbol{x})$ given by equation (5.4) below:

$$\boldsymbol{P_N(X \geq x) = \int_x^\infty \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-\mu)^2/(2\,\sigma^2)}\,dx} \qquad (5.3)$$

$$\boldsymbol{P_N{}'(X \geq x) = \int_x^\infty \frac{1}{\sigma\prime\sqrt{2\pi}} e^{-(x-\mu\prime)^2/(2\,\sigma\prime^2)}\,dx} \qquad (5.4)$$

We use those two equations to calculate the probability related to the physical exercise duration without our system, comparing to the probability of exercising when making use of it.

Table 5.4 summarizes the probability that a given user spends a duration in minutes between values a and b in physical activity. For example, without the system, the probability that a given individual spends a duration between 15 and 20 minutes exercising is 0. With the system, the probability that a typical participant spends a duration between 15 and 20 minutes is 0.139. Let us consider the probability that the physical activity during an exercising session, equals or exceeds the threshold of 15 minutes. This results in the values computed below for each participant.

-- Participant 1:

Without the system, the probability that the participant spends a duration greater than 15 minutes is 0. With the system, the probability that the same participant spends a duration greater than 15 minutes is 0.9693.

$$\boldsymbol{P_{N(\mu=7.4,\sigma=1.34)}(X \geq 15) = 0}$$

$$\boldsymbol{P_{N(\mu= 25.2,\sigma= 5.45)}(X \geq 15) = 0.969}3$$

-- Participant 2:

$$\boldsymbol{P_{N(\mu=5.4,\sigma=2.88)}(X \geq 15) = 0.001}$$

$$\mathbf{P_{N(\mu=22,,\sigma=2.35)}(X \geq 15) = 0.998}5$$

-- Participant 3:

$\boldsymbol{P}_{\boldsymbol{N(\mu=8,\sigma=2.74)}}(\mathbf{X} \geq \mathbf{15})$ =0.005

$\mathbf{P}_{\mathbf{N(\mu= 29,\sigma=4.42)}}(\mathbf{X} \geq \mathbf{15})$ =0.9992

As we can see from the values without and then with the system, it is very promising to obtain good results with the system in terms of physical activity session duration.

5.7.2. Estimation of exercise frequency

In this section, we compare the frequency at which a given subject usually exercises without the use of our system, to the frequency he is likely to exercise when using our system. For this we define out probability model as follows. We consider the two random variables X_1 and X_2 such as:

X_1: random variable representing the number of times a participant exercises weekly without the system

X_2: random variable representing the number of times a participant exercises weekly making use of the system

We assume X_1 and X_2 follow a Poisson distribution with rates λ_1 and λ_2 respectively. From the experiment, we have empirically computed rates λ_1 and λ_2. λ_{1p} for each participant is the average number of times a participant exercises within a week, pre-system. And λ_{2p} is the average number of times a participant exercises within a week using our system. We computed the rates for each participant and then took the average for all participants. We found:

λ_1 = 1.727272727 λ_2= 5.363636364

The probability formula for Poisson distribution is given by:

$$P(X_1 = n) = \frac{e^{-\lambda_1} {\lambda_1}^n}{n!}$$

From which we obtain:

$$\boldsymbol{P(X_1 \geq n) = \sum_{k=0}^{n} P(X_1 = k) = \sum_{k=0}^{n} \frac{e^{-\lambda_1} {\lambda_1}^k}{k!}} \quad (5.5)$$

$$P(X_2 = n) = \frac{e^{-\lambda_2} {\lambda_2}^n}{n!}$$

Likewise, we obtain the formula:

$$\boldsymbol{P(X_2 \geq n) = \sum_{k=0}^{n} P(X_2 = k) = \sum_{k=0}^{n} \frac{e^{-\lambda_2} {\lambda_2}^k}{k!}} \quad (5.6)$$

We use the formulas (5.5) and (5.6) to compute the probability values, as shown in Table 5.5.

Table 5.5 shows that, without the system, the probability that a participant performs physical activity at least once a week is $P(X_1 \geq 1) = 0.51$, while it is almost guaranteed that all participants exercise at least once a week with the system $P(X_2 \geq 1) = 0.97$.

The table also shows that, without the system, the probability that a participant exercises at least twice a week is 0.25, while the same probability reaches 0.9 with the system.

Finally, the table shows that the probability that a participant exercises at least five times a week without the system is almost zero, while the same probability is 0.45 with the system.

Table 5.5
Probability of exercise frequency assumed to follow Poisson distribution for the three participants.

	$P(X_1 \geq n)$	$P(X_2 \geq n)$
$n = 1$	$P(X_1 \geq 1) =$ 0.5151766	$P(X_2 \geq 1) =$ 0.9701937
$n = 2$	$P(X_1 \geq 2) =$ 0.2499929	$P(X_2 \geq 2) =$ 0.9028199
$n = 3$	$P(X_1 \geq 3) =$ 0.0973114	$P(X_2 \geq 3) =$ 0.7823638
$n = 4$	$P(X_1 \geq 4) =$ 0.03138074	$P(X_2 \geq 4) =$ 0.620843
$n = 5$	$P(X_1 \geq 5) =$ 0.008604696	$P(X_2 \geq 5) =$ 0.4475753

5.7.3. Quantitative Potentials

The green energy donation system's potential better stands out when we consider its adoption at a national level. Rich countries such as Canada and US have a serious obesity problem, but have high electricity consumption rates [94] and will not benefit very much from the human generated energy. On the other hand, poor countries do not usually have obesity and overweight problem, but have very low electricity consumption [94] and a pronounced need for energy donations. The two profiles match together perfectly in a win-win combination.

In this section. We evaluate the potential of the proposed system if it is adopted at a country level. Let us consider for example Canada, which is one of the world's most overweight countries. The Canadian population is just above 35 million as per the Statistics Canada [96]. The percentage of the adult population is of 80.6% [96]. So the adult population is of about 28 million. Let us suppose that about 10% of the adult population adopts the proposed system, and calculate how much green energy can be donated to a country such as Haiti for example.

We know from the experiment that we did that an average person is able to sustain energy generation for about 20 to 30 minutes. Although the watts generated depend on the equipment and on the intensity of exercise, we will use our experiment results as a guideline, as we are seeking more an approximation than an exact number of how much green energy would be generated by a group of the population. During the experiment, we found that the participants who were pedaling with more intensity were generating what averages 300wh, and usually stopped at 20 minutes or just above that. While those participants who went for 30 minutes or over were pedaling at a slightly lesser intensity and producing around 200wh. So they produced about 100watt in the half-hour exercise session. Hence, we will go ahead and consider the 100 watts generation per session as an average since our participants lead a sedentary lifestyle, and so some people will be able to produce more, but some others probably less if they are older for example. Assuming the system users exercise 5 times a week then every person will produce 500 watts of green energy per week. Over the course of a year this will amount to 26 kwatts. At a country level considering the 10% of the adult population, the amount of green energy produce will be 73.34 million kwatts.

The consumption in Haiti is of 38kwh per capita. By dividing the green energy produced by the consumption per capita in Haiti, we obtain 1.93 million. So almost 2 million people in Haiti can benefit from full electricity provision for the year long, in addition to this being green energy, and in addition to it having made millions of the donating adult population healthy.

As a second example, we will consider US. as a donating country. The population of US is 327 million as per the United States Census Bureau. The percentage of the population 18 years and over is of 76%, which is 248 million adults. As per the National Centre for Health Statistics, 70.7% of adults 20 years of age and over are overweight, including obesity[97]. If 20 percent of the adult population uses the green energy donation system, then following the same logic above with 5 exercise days a week, 24 million adults will each donate roughly 26 kwh a year. This amounts to 1.92 billion kwh per year. One of the poorest countries of south America is Bolivia with an electricity consumption is of 752kwh per year per capita[94]. Green energy donations can light up homes for 1.7 million people in Bolivia for a full year.

An analysis done by the Charities Aid Foundation (CAF) at the international level, ranked 24 countries in terms of the rate of charitable donations by individuals as a percentage of the gross domestic product (GDP) [98]. The findings of this analysis rank USA, New Zealand and Canada as the top three countries in terms of charitable donations. This shows that these populations have the social good spirit and are very likely to be motivated by the donation aspect of the system and adopt it, which also explains the highly promising results we obtained during our user experiments.

Chapter 6. Digital Twin for Mental Well-being

Physical well-being is the first area usually focused on when it comes to health and well-being, but overall wellness goes beyond the physical body to include mental wellness. Indeed, it is now well recognized that a wide range of illnesses are caused by mental distress. Many factors can contribute to human mental stress, especially in our modern lifestyle, among which the use of electronics and notably the use of smartphones. Indeed, their usage is becoming prevalent among people generally and young users specifically.

Many studies have been dedicated to assessing the impact of smartphone usage on the mental well-being. All of these studies as we have found in literature rely on reported usage by users themselves. As we have discussed earlier in this thesis, self-reported data is inaccurate [3], [4] and can only be trusted to a limited extent in research studies. It is worth mentioning that this fact was confirmed later by our study, during which we also collected reported usage from our participants and compared it to the tracked usage, and found them to be different in the majority of cases studied.

6.1. Method

The digital twin concept, with its methodology of tracking the real twin directly using personal devices is very helpful and even crucial here if we want to study the mental well-being of a population. We have thus dedicated a section of this thesis to the study first hand of the smartphone usage and the assessment of its impact, be it positive or negative, or a mix of both, on mental well-being. We have partnered with a team of psychology researchers at the University of Ottawa for this purpose.

In this case study, we adopted the following methodology, in accordance with the digital twin requirements defined in Chapter 1. First, we collect data about smartphone usage. To achieve this, we need to track the usage on the smartphone itself. We aim for as much detail as possible, as long as the users' privacy is respected, such as tracking apps usage but not tracking any content. This data is encrypted and transmitted using secure connection to our cloud server daily for storage and analysis. Visualization of data trends is to be made available to the users or psychologists in order to see how the smartphones are being used throughout the day/week/month etc. This is an important component of the system, but we have not made this visualization available to our study participants during the study itself, in order not to influence the smartphones usage after participants become aware of it. But for the after study, these data visuals can be made available to users to look at in order for them to see for themselves how much usage they make of their phone and how this is affecting their mental state, as well as other parameters such as their performance throughout the day, their sleep, their relationships etc.

In order to match the smartphone usage to the mental well-being of users, we used a survey developed by the psychology team. This survey was put together specifically for this research study and contains questions about the person's mental state. Detailed questions in the survey have to do with the person's mindfulness, self-regulation, emotional, psychological and social well-being etc. This survey is to be filled by users every month. We have integrated this survey in the mobile tracking app itself, for easy access by the users and so they can fill it at their own time. Data collected is transmitted to our server as well for storage and later analysis. Figure 6.1 illustrates the Digital Twin Architecture as shown in Chapter 3, with an emphasis on the mental well-being case study.

As shown in this figure, the personal device that is used to track the real twin’s well-being is the smartphone itself. Since there is currently no standard available to unify the data format specific to reporting on smartphone usage, we transmit this data to the non-X73 communication module of the digital twin system. This data is collected using a mobile app that we designed and developed to this effect, and that is detailed in the next section.

6.2. Mobile App Design

6.2.1. Purpose of The Mobile App

We designed and developed a mobile application that serves mainly two purposes: first, it presents users with a convenient way to fill-in surveys on their own spare time, wherever they are, without time or space constraints, since the app is installed on their mobile phone. The app also allows them to start filling a given survey and go back to it whenever their time permits. It also allows researchers to collect data automatically by having it transmitted from users’ smartphones to the server without researchers’ further intervention.

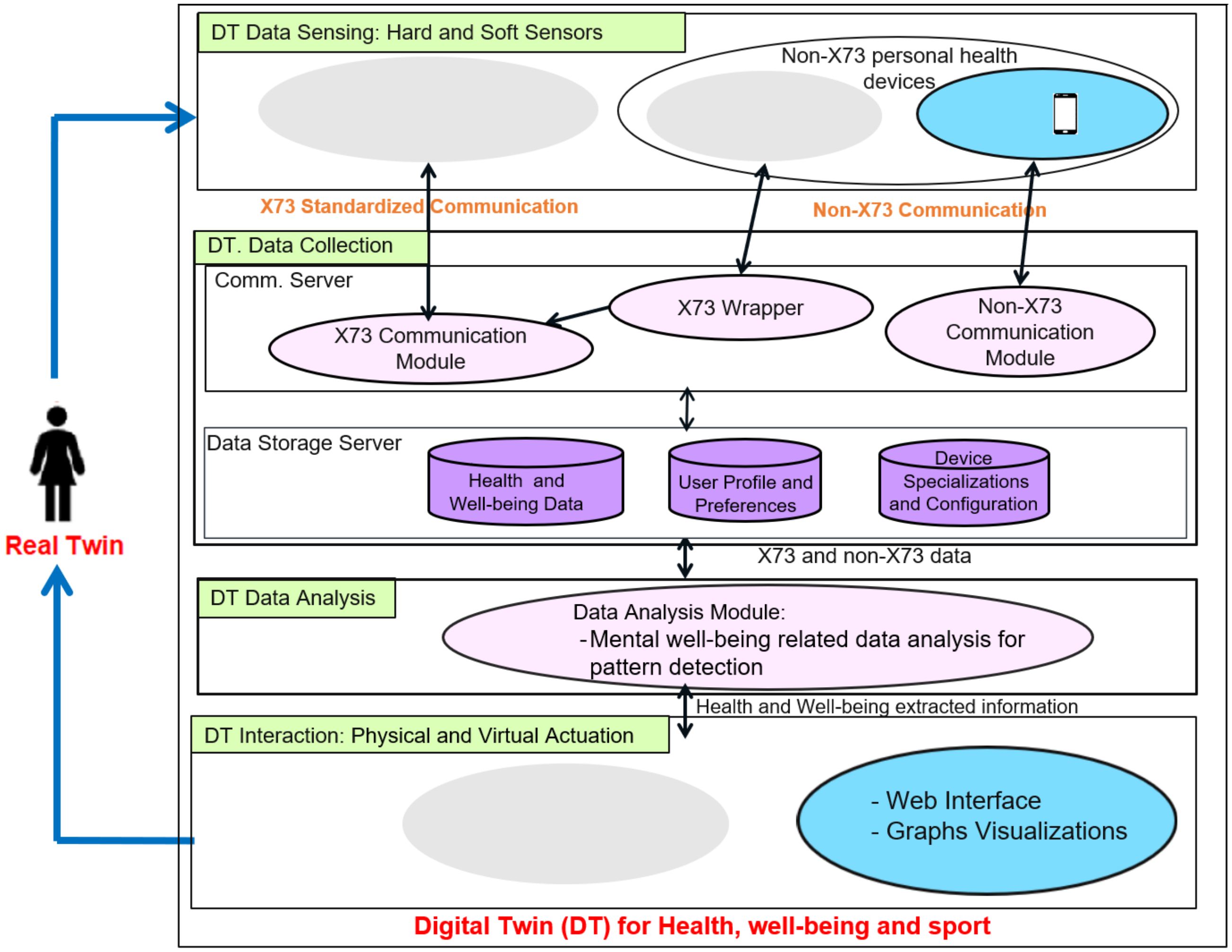


Figure 6.1. Mental Well-Being Case Study System Architecture (adapted from Figure 3.2 and hence components non-relevant to this case study are faded out)

The second important aspect of the app is that it tracks individuals’ phone usage in the background, without interfering with their user of the phone or influencing it in any way. In this regard, the app tracks the apps used, the time an app is used, as well as the duration of usage.

6.2.2. Smartphone Usage Tracking

It is generally hard for individuals to estimate how much use they make of their phone, as well as how they use it every day. So instead of relying of reported usage by individuals, we decided to track it directly on their smartphone. This way, we collect data that is more accurate and send it on a regular basis directly to our server over a secure connection.

After the users install the app, they create an account and login using their credentials. They fill-in a demographic survey only once. Then phone usage tracking is carried out and monthly surveys about mental well-being are requested in order to study how the different phone usages are affecting users. The modules designed and implemented for the mobile app are shown in Figure 6.2. In order to collect tracking data, we used the Android Api that reports a list comprising the usage for all of the apps. The app also automatically prompts the users to complete a mental well-being survey, with monthly reminders, as necessary.

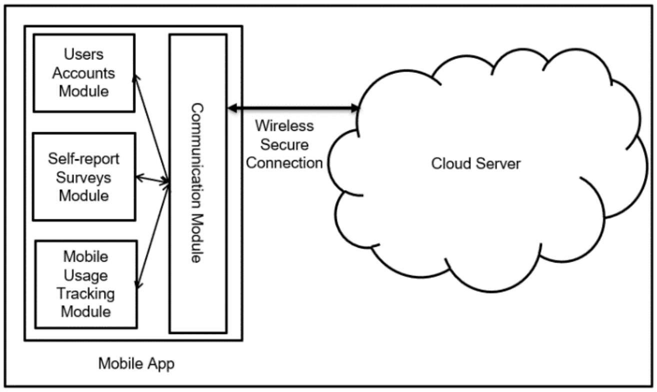


Figure 6.2. Mobile App for Smartphone Usage Tracking

Data storage and data analytics are then carried out on the server in the cloud, to find patterns pertaining to smartphone usage and its impact on well-being. We also designed a web interface to allow for visualization of usage trends for daily, weekly and monthly usage. These are made available to users and possibly to psychologists, although during the user study that we conducted, we did not give access to it to our participants, for the purpose of avoiding that participants change their usage habits which would affect the study results.

6.3. User Study

We conducted a user study that focused on an athlete's population among university students. This study serves mainly as the pilot of our system, allowing us to generate preliminary results. To achieve this, we conducted a 15 days pilot study with five student-athletes. Research studying smartphone usage related to sport or physical activities relies on user reported usage with no actual tracking. In this study, we use the smartphone as a personal device that can give us insights on the influence of smartphone usage on athletes' mental well-being by tracking the usage directly on the phone itself. The study was conducted among a population of athletes, with the main objective of collecting data related to the smartphone usage in the domain of sport, and analyzing it in relation to mental well-being. The choice of this population of young adults was mainly because they are required to perform in both sport and university or college academics. These requirements can cause stress and illnesses, but this depends on the student-athletes self-regulation skills. Thus, it is important to study these skills in this population along with other psychological variables, and in particular, how they are influenced by smartphone usage. Seven participants took part in the pilot study. One participant dropped out due to time constraints, and one participant did not complete the surveys required for the period of time under review. Hence, we report on five participants in this study results, one male and four females. These participants are student-athletes at the University of Ottawa, playing competitively in basketball, flag football, track and field, and ultimate Frisbee.

6.4. Results

In this study sample, tracking the smartphone usage showed an average daily usage of 4.5 hours. The usage varied from 20.5 hours to 119.4 hours during the 15 days of the study, with a weekly average of 31.7 hours. The reported smartphone usage by participants was lower than the tracked usage, except for one participant whose reported and tracked usage were close.

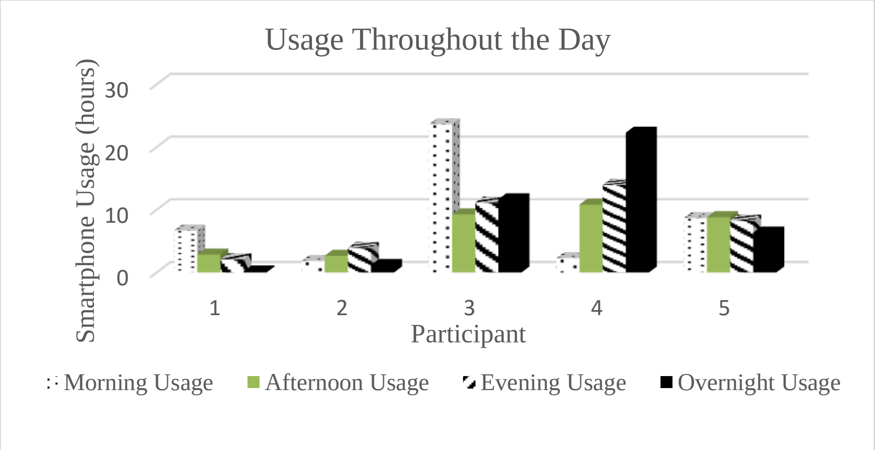


Figure 6.3. Smartphone usage over four periods of the day.

It was also interesting to study the trends of smartphone usage in different periods of the day. For this, we split the usage periods into four periods which are morning, afternoon, evening and overnight. These correspond respectively to the periods of 6am to 12pm, 12pm to 6pm, 6pm to 12 am and 12am to 6am. The usage during these four periods is shown Figure 6.3. We found that the usage of four of the participants was noticeably higher either in the morning or overnight comparing to other times of the day, however it was not very different during other times of the day. One participant had a particularly high overnight usage representing 45% of his total usage, and was our only participant reporting a mental illness.

Table 6.1.

App Usage Distribution

Participant	% Top 3 Apps	% Other Apps	Total hours/week
1	80.50	19.50	11.79
2	59.04	40.96	9.56
3	60.95	39.05	55.7
4	59.16	40.84	49.32
5	75.44	24.56	32.12

Next, we studied the top used apps during the 15 days of the study. We found that for all the athletes, the sum of the weekly usage of the top three apps represented more than 50% of their total weekly usage, as can be seen in Figure 6.4. We also found that at least one social media app was among the three top used apps for all athletes. Social media apps used by our participants involved Snapchat, Instagram, and Facebook. And a social media app was actually the most used app for four of the athletes. These athletes' use of the social media app was much higher than their next most used app, such as 7 hours or more. The athletes' smartphone usage, including the top three apps as well as the rest of their used apps and the total usage per week, is shown in Table 6.1. Besides, we noted that the average phone usage time for participants was higher than their reported time spent either studying, training or working. Indeed, the weekly average phone usage was about 31.7 hours, while the reported time spent studying was 20 hours weekly on average, and time spent training was 11.4 hours weekly on average.

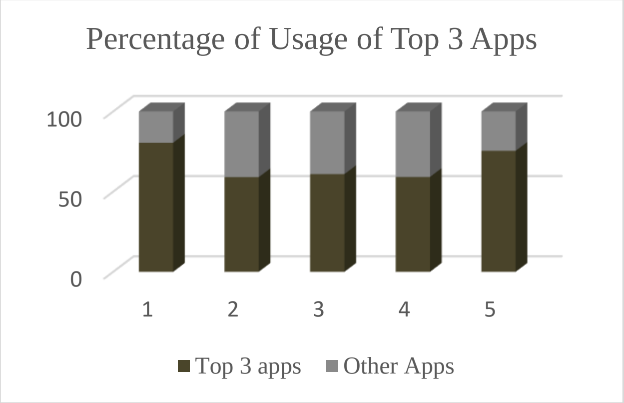


Figure 6.4. Percentage of usage of top 3 apps (per week)

Besides, four of the athletes scored as flourishing, which is a state of positive self-perceived success. Furthermore, all athletes in this sample were found to have moderate to high survey scores, based on their responses to the psychological well-being survey included within the mobile app. This survey includes questions in each of the three areas of mindfulness, self-regulation and mental health. We found that in this sample of athletes, four athletes scored high on all three areas and one of them moderate in all three areas. For the four athletes who scored higher, self-regulation scores ranged between 65.2 and 84.8, mindfulness ranged between 75 and 78.8, and mental health between 60 and 86.2.

6.4.1. Limitations

This study presents interesting findings, although it has some limitations. Indeed, our sample is small as we included 5 athletes in the current study. On the other hand, our mobile app is only available for Android devices. This means that we did not include any iOS mobile phone users in this study sample. However, iOS users may present different phone usage patterns.

6.4.2. Potential Directions in DT for Mental Well-Being

We found that there is a high amount of data collected by the usage tracking, which requires many calculations to extract phone usage. We have developed algorithms to analyze the data and based on our experience, we are planning to merge two different Android APIs to facilitate usage tracking for our next study. This pilot study also allowed us to take into account the participants comments about the system, to make it even more user friendly in preparation for our next study, which is a longer range study spanning 8 months. The objective from this longer term study is to assess how changes in smartphone usage, overtime, affect mental well-being and sport performance. Achieving this will allow our digital twin system to generate user feedback, to make the real twin aware of their current phone usage and how it is potentially affecting their mental well-being and success in sports.

Chapter 7. Digital Twin for Sport

We used the personal health devices standardized as detailed in Chapter 3, in order to collect information about the real twin and feed the sport profile of the digital twin. On the other hand, we used the collected information to assist in the training of athletes in the sports domain.

7.1. Athlete Training Automation

The objective here is the application of the Digital Twin to sport training to study its potential to benefit the athletes and assist coaches. We propose achieving this by the use of standardized wearables as described in the previous chapter, in an athlete training system. We transfer data related to athletes' training to the cloud, store it, and allow for its visualization by athletes and coaches. Since the data communication process is standardized following IEEE/ISO 11073, this makes it possible for coaches and/or physiologists to follow up on athletes' quality and duration of training as needed. The use of personal health / sport devices in order to monitor the athlete can then be leveraged and its benefits maximized.

Technology has been steadily making its way into sports for the enhancement of athletes training. One of the sports that can benefit from the use of technology in sport is soccer. An important part of training in soccer -as well as other sports- is sprinting, as it is a high intensity exercise that increases athletes' performance in ways that soccer-specific training routine does not address. It is a crucial part of soccer training because, among other important benefits, it increases the athlete's speed bursts abilities. Indeed, every soccer match will require players to perform many sprints and if the player has not participated in speed training, they will fatigue quickly. In this chapter, we present a haptic automated sprint training system for soccer players. Our system can be personalized by a coach as recommended for each athlete, and the athletes can then use it independently to perform the training. The coach can use the system to monitor and analyze the athletes' performance. Preliminary tests and analysis of the proposed system show promising results.

Sprinting is an established training technique used in many sports as an efficient method to improve athlete performance. It is used by athletes to build strength and power as well as speed. Unlike aerobic exercises like running, walking or swimming, sprinting is an anaerobic exercise which is a high-intensity, very short duration physical activity with a high demand for oxygen, and using energy from contracting muscles [99]. Indeed, the oxygen delivered by the inhaled air as a source cannot keep up with the high oxygen demand given the intense nature of the anaerobic exercise. This means that in this case, the oxygen demand exceeds the oxygen supply. Hence, fuel from muscles is used to provide a rapid energy source, by breaking glycogen down into glucose and converting it into energy. This process results in a build-up of lactic acid in the muscles as a by-product and explains the quick exhaustion. Regularly performing anaerobic exercise training like sprinting or push-ups, increases the body's ability to tolerate lactic acid which increases the athlete's performance.

Types of anaerobic exercises include sprinting and weight training. Both types of exercises will build muscle and strength, but weight training works on one body part at a time while sprinting has the advantage of working on building many muscles simultaneously, which makes it one of the most efficient anaerobic exercises. Furthermore, sprinting also increases speed bursts, which are crucial to athletes during sports games such as soccer or hockey where speed can be a determining factor to winning.

Sprinting is thus a vital part of soccer training, because in case a player uses only aerobic exercises as his soccer training, he will experience an early onset of fatigue during the game which will inhibit performance, as players are required to sprint often during matches. However, his body would not be used to the anaerobic performance.

Figure 7.1. Athelte sprinting wearing the haptic insole, as part of his soccer training

Figure 7.1 shows participation of a soccer athlete in speed training where strenuous physical exertion is carried out in a very short period of time measured in terms of seconds, propelling the whole body forward with the help of forceful arms swings, giving the athlete a completely different workout than the one he gets from his usual soccer training routine.

We propose a haptic athlete sprint training system to automate the sprint training. Haptic feedback is already well established in many domains, and its use in the domain of sports has just started to emerge in recent years with the potential to make a positive contribution to athletes' sport performance. Our objective is for this system to be a step towards this achievement.

7.2. Athlete Training System

7.2.1. Concept

Sprinting is established as an athlete's performance improvement training is many sports, among which soccer, where sprinting has proven to be effective [63]. Indeed, it is used in athlete training for its potential to improve speed performance, among other benefits. Aerobic exercise can improve the endurance which is important for game play, but anaerobic exercises such as sprinting, can improve the acceleration in athletes which is crucial in making the difference between good and average players, for its benefits in improving the overall performance.

Some of the sprint training benefits for soccer include speeding towards the ball, competing against a player from the other team, breaking away from defense, or preventing offensive players from getting past. The coach thus needs to get every athlete to sprint. However, this is a skill that athletes can practice on their own time, guided by an automated system configured as recommended by the coach.

Anaerobic exercise involves short bursts of high-intensity exercises, interspersed by periods of recovery. In our system, we aimed at incorporating two kinds of anaerobic exercises: sprinting as well as push-ups, and we used walking to allow for a recovery period. Sprinting involves a short burst of running at full speed, followed by a short interval of push-ups and then a period of recovery. In a regular training, if the coach is incorporating sprinting exercise into the training session, the coach would give verbal instructions to the athletes during session, for them to follow the sprint training. Our system serves as a coach assistant allowing him to set a system configuration, which is then used by the athletes to train on their own following the coach recommendations. The coach can later check the athletes training in the system.

In order to give the athletes a signal to start training and switch between sprinting and recovery periods, we opted to use both an audio signal as well as a vibrotactile wearable device. Vibrotactile systems are in use in a variety of domains, and are finding their way into the field of sports.

On the other hand, we also collect training data and transfer it to the system to allow the coach to monitor the athlete's training. For that, we not only save the training session data on a cloud-based server so the coach can see the progress, but we also collect gate related features so the coach can also monitor the sprinting performance assisted by our system. To do so, we use an X73 smart insole to collect data related to foot pressure points. The use of a smart wireless insole is efficient and practical because unlike other studies that used treadmills for data collection and analysis, the insole is mobile and allows for collection of plantar pressure data during outdoor training as well as during live game play. A post performance analysis of collected data is then done by the coach using our system's data visualization to provide the athlete with feedback about their training.

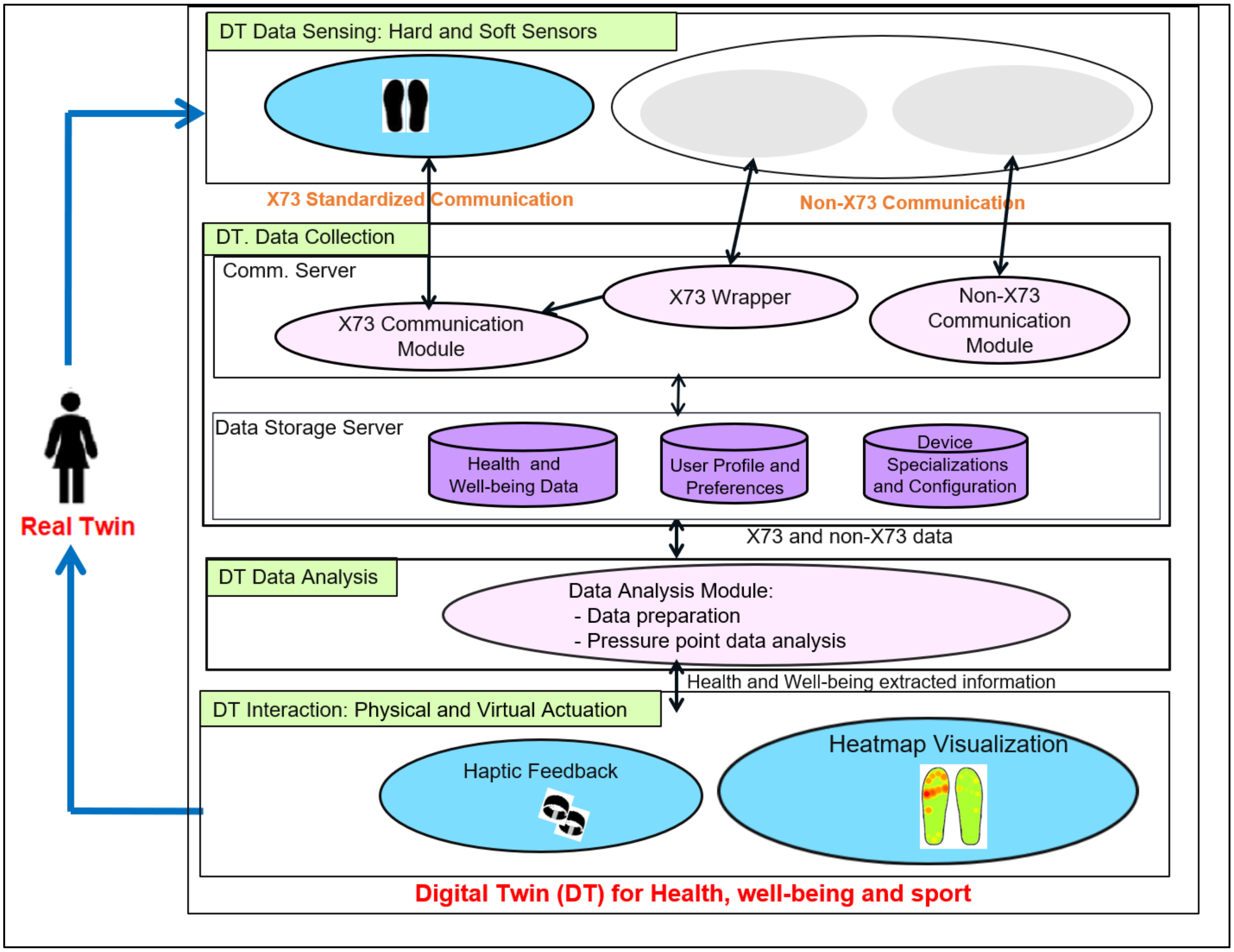
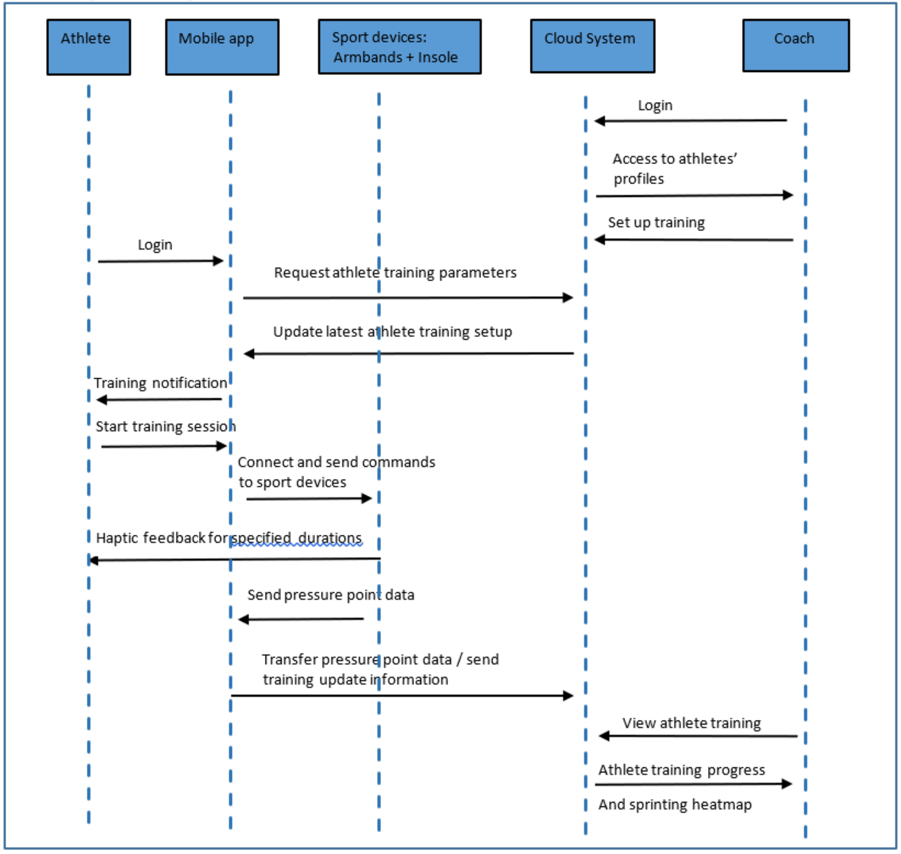


Figure 7.2. Sport Case Study System Architecture (adapted from Figure 3.2 and hence components non-relevant to this case study are faded out)

7.2.2. The Digital Twin for Sport

The architecture of the digital twin for sport is illustrated in Figure 7.2 following the digital twin architecture presented in Chapter 3. Figure 7.2 shows the use of two wireless haptic armbands, a pair of wireless X73 smart insoles, a mobile application and the cloud-based server. The haptic arm-bands are the devices that are in direct contact with the athlete, and which signal to him the time to switch the exercise types. The system allows the athlete to follow the sprint training as specified by the coach, but at their own time and without the presence of a coach. He can perform a series of sprints followed by push-ups followed by walking at a comfortable pace for recovery, and starting over with the same sequence of sprinting – push-ups – walking, for the number of times specified by the coach.

We extended the mobile application to this effect as shown in Figure 7.4. It uses the parameters related to the speed interval training as configured by the coach. These parameters' values are fetched from the server and are displayed on the mobile app screen. Our system can be personalized by a coach for both the duration and number of drills recommended for each athlete, and the athletes can then use it independently to perform the training. The system UML sequence diagram summing up the main flow of interactions is depicted in Figure 7.3. During a training session, the mobile app communicates wirelessly using Bluetooth with the personal devices. It also uses X73 standard communication with the X73 smart insoles. Haptic feedback is already well established in many domains, and its use in the domain of sports has just started to emerge in recent years with the potential to make a positive contribution to athletes' sport performance.



UML Sequence diagram

Figure 7.3. System UML Sequence Diagram

The mobile app sends commands via Bluetooth to the armbands to provide the user with signals for the training instructions. This is in addition to audio messages played on the app itself, providing the same instructions by means of voice signals. The first set of armband vibration signals the beginning of the sprinting period. The first armband keeps vibrating for the duration specified by the app, which is the same as the sprinting duration set by the coach. Then the first armband stops vibrating and a command is sent to the second armband, which signals the beginning of the push-ups period.

Likewise, the second armband vibrations last for the duration specified by the coach for push-ups. Following this, the second armband stops vibrating, and this signals the period of recovery during which the athlete is walking, until the start of the next set of vibrations. The cycle will repeat depending on the number of drills set by the coach, then both armbands will vibrate simultaneously three times, signaling the end of the exercise session.

The other personal device used in our system for athlete training is the X73 smart insoles, as shown in Figure 7.5. This wireless smart insole has been designed specifically for sport and wellbeing [100]. And it has been validated with Tekscan Strideway mat system with successful results [101]. It was developed using 12 force-sensitive resistor sensors FSR-402 that can measure force or pressure, as well as an inertial measurement unit (IMU) containing an MPU-9250 motion processor that measures gyro and acceleration data. The data is controlled using an ESP-8266 microcontroller with Wi-Fi capabilities. A Bluetooth module is also added for direct communication with the mobile app. The layout of the force-sensitive resistor sensors embedded in the smart insole is shown in Figure 7.5. We use this insole as part of the system presented here, in order to collect plantar foot pressure during the sprinting training. We store the data on our cloud-based server and subsequently generate heatmaps that allow the coach to analyze the sprinting performance of the athletes and suggest any needed improvements. Preliminary tests and analysis of the proposed system show promising results.

Start: 12:18:25 Finish: 12:23:17

☑ Vibrator ☐ Sound

Name: El Saddik Cycles: 4

6 Sec.

6 Sec.

60 Sec.

Figure 7.4. Mobile app interface

7.3. User Study

To evaluate our system, we conducted an experiment with a total of six participants. This experiment was carried in two steps. First, we performed a usability study with three participants and collected their answers to our survey, and we took the survey results into account in our system for the next step. Following this, the second step was to conduct an experiment with three young athletes from a soccer team. We discuss the results in what follows.

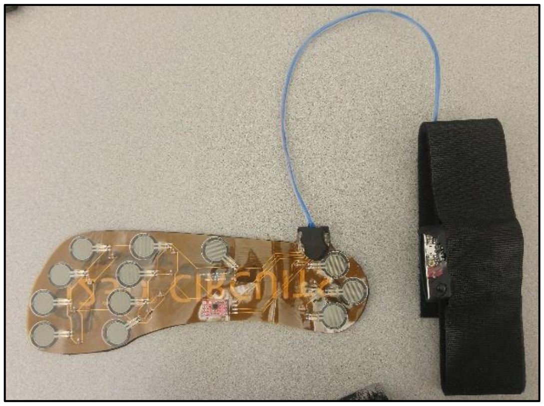


Figure 7.5. Smart insole to capture plantar pressure

7.3.1. Usability Study

We conducted a usability study with three participants before the actual experiment with athletes. In fact, the system as we had initially designed it, contained vibration motors connected to the insole itself, instead of the armbands, to signal to the users the start of sprinting exercise. During the user study, we first explained to each of the participants how the system works and what is expected from them, which is mainly to follow the vibrations signals, in order to switch from one exercise type to the next. The sprinting duration, the push-ups duration as well as the walking recovery duration are configurable following the coach's recommendations, but here we used our default values set respectively to 6 seconds based on the finding in [64], 6 seconds and 60 seconds. Each of the participants put on a pair of the smart insoles, and started the exercise.

Figure 7.6. Haptic armbands to send vibrotactile signals for athlete traininng

The feedback from our users about the training system using our mobile app was mostly positive. However, all three participants declared that the vibrations on the sole of the foot could only be felt while standing but could not be felt clearly while running which hindered the following of exercise instructions from the system. Based on this observation from our participants, we modified our system set-up into two vibrotactile armbands shown in Figure 7.6s instead of the vibration motors initially connected to the insole. We then conducted a new user study with the same participants, this time using the modified set-up following the findings of the first experiment. This time we had very positive feedback from our users.

7.3.2. Experiment with Soccer Athletes

Based on the findings of the first user study, we performed an experiment with the participation of three young soccer athletes. Before the experiment, they were asked to put on a pair of smart insoles and both armbands, shown respectively in Figure 7.5 and Figure 7.6. A short introduction to the procedure to follow was given to each of them, with the explanation of the objective from the system as a trainer assistant they can use at their own time, and instructions on how to use the app, and finally a brief sense of what the vibrations from the armbands feel like so they know what to expect. Although the objective of the mobile app as it was designed, is to convey to user signals of the starting of exercise session, exercise types and end of exercise session by means of vibrotactile equipment, we do provide in the mobile app both options of vibration signals and/or audio signals, as can be seen on Figure 7.4. For the experiment, we turned on the audio signals, in order to collect participants feedback on the both types of signals.

Each athlete would start the exercise session when they are ready, which first plays the sound “sprint” on the mobile app in parallel to starting the set of vibrations on the first armband. This lasts 6 seconds (this could be a different duration if set by a coach). Then the vibrations on the first armband stop and the sound “push-up” is played on the app while vibrations on the other armband carry over indicating the start of the push-ups exercise which also lasts for 6 seconds. Following this, the sound “walk” is played and both vibrations stop for a duration of 60 seconds set for recovery. At the end of this experiment, the participants were invited to fill in a survey for system evaluation.

7.4. Experiment Results

7.4.1. Evaluation Survey Results

The post study questionnaire showed promising interest in this automated training system. On a scale from 1 to 10, 10 being the most effective, the participants rated the system between 8 and 10, with an average rating of 9. The athletes found the vibrotactile signals used in this experiment to be very effective, while the audio was described as unnecessary, with one of the participants saying that the vibrotactile signals give flexibility to have headphones on, in which case he would not hear the voice instructions. They rated the level of comfort related to wearing the devices between 7 and 9, which is a very positive rating given that we did not give any special consideration to device esthetics or comfort of wear.

All participants declared that they are interested to use such a system to train following the coach recommendations, but on their own time. In this post evaluation questionnaire, participants also reported that this system is valuable for outdoor training where voice instructions can be difficult to hear, while vibrotactile signals allow them to switch exercise type effectively.

7.4.2. Sprinting Pressure Results

We used the data collected by the smart insole and transferred to the cloud-based server to generate graphs and heatmaps related to athlete sprinting.

Figure 7.7 shows the plantar pressure measured by the FSRs built into the smart insole, and standardized to the body weight as suggested in [102], in order to study the athlete’s foot pressure during sprinting. In [102], sprinter athletes’ performance was compared to performance of non-sprinter athletes. Other than the sprinter athletes being faster, findings showed that the sprinter athlete had a more forceful contact with the ground after standardization to the body weight, and that the duration of contact with the ground was shorter.

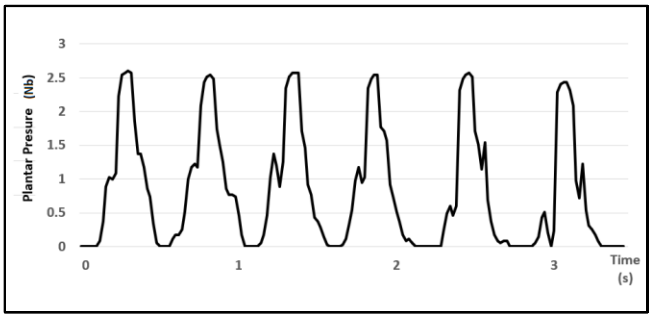


Figure 7.7. Athlete plantar pressure during sprinting

Furthermore, a study published in [103] suggest that faster athlete sprinters have a distinctive way of a more forceful contact with the ground at the time of initial contact. These studies show that distinct patterns of foot pressure can help speed train a soccer athlete for a higher performance in the soccer field.

Figure 7.8 depicts the pressure heatmaps resulting from two sprinting steps for one of our athlete participants. The red color in the heatmap shows the highest pressure followed by the orange, yellow, and then the green color show very mild or no pressure. During the first sprinting step, shown in Figure 7.8 (A-1), the right foot is on the ground and the left foot is lifted in the air, and the little bit of pressure that is seen on the left side heatmap is caused by the contact of the foot sole with the shoe. Likewise, Figure 7.8 (A-2) shows the heatmaps when the opposite foot is on the ground. Figure 7.8 (B-1 and B-2) show the two steps only for the foot that is in contact with ground, and omitting the foot that is lifted each time.

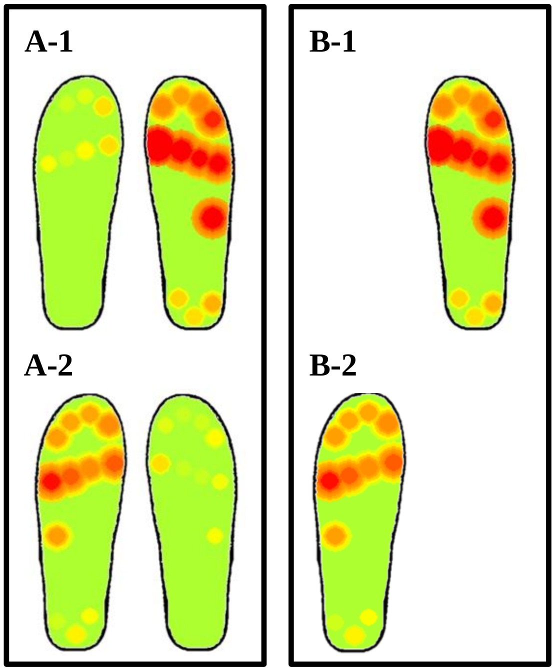


Figure 7.8. Athlete sprinting steps pressure heatmaps

After visualizing data on the server, the coach can give recommendations to his athletes both for improvement as well as from an injury prevention perspective. For example, if the sprinting heatmaps show too much pressure on the heels, then the coach may want to give the athlete in question advice on how to lower that pressure and switch to a forefoot strike in order to increase their speed and avoid injury. From the heatmaps in Figure 7.8, we can see that the pressure the athlete is applying on the right foot is higher than the left foot. This is something that can hardly be noticed while an athlete is running but that can be detected with the analysis of the visualization provided by the system presented in this chapter.

7.4.3. Study Limitations

Some limitations for this study exist, notably that the athletes' sample was small and results obtained can only be conclusive in that the system is promising, not as a proof of its effectiveness. Given the positive findings with a small sample, a future study with a bigger sample size is worth conducting for more decisive results.

7.5. Conclusion

In this chapter, we have presented a sport application of the digital twin system that serves as an athlete training assistant. It is used by the coach to set the recommended training parameters for the athlete, and then by the athlete to follow their training. The system is totally portable as it uses a mobile app to lead the parameters from the server and wireless vibrotactile armbands and a wireless pair of smart insoles. Training data is transferred to the server to be reviewed by the coach on his own time. Results from the experiment show promising results which is encouraging in terms of use of technology in sport.

Chapter 8. Conclusion and Future Work

In this research, we proposed a digital twin framework for health, sport, and well-being. This work aims at improving the well-being of individuals through continuous monitoring using sensors as part of the data collection process. This data is then stored, analyzed and feedback is provided to the real twin through physical and virtual actuation which serve as an incentive to get the real twin to be physically active, to be socially contributing and to be aware of their mental well-being and its possible influencing factors. Benefits extend to the domain of sport where the real twin can for example get automated training at their own time and convenience.

We have designed, implemented and conducted case studies in each of the areas of health as defined by the world health organization. These case studies served as prove of concept in the areas of physical, social and mental well-being. We also conducted a case study in the domain of sport to evaluate the system potential in this health-related domain. These studies helped explore some of the possibilities where the digital twin system can serve his real twin's well-being.

As stated above, the main aim of our proposed DT framework is to improve the well-being of individuals. Future work may focus on extending or expanding the proposed framework in one or more of the following ways:

8.1. Improve Data Collection and Standardization

- Collect more types of data such as blood pressure, body temperature, sleep data, some of which we are already collecting (such as sleep related data) but not making full use of yet. The more data we collect about the real twins, the more patterns we find about what affects their health and well-being positively or negatively, to help them gain more insights on contributing factors to their state of health.

- Another promising area in our future work is including soft data sources, such as social media data, and use it in data analytics. This will improve the impact of the system on the real twin through a better capacity of the digital twin to gain deeper insights on the real twin's lifestyle and preferences. For example, social media connections and profile similarities can be used to derive motivational feedback that "worked for others" and suggest it to the real twin. As we know, collecting shopping patterns has served in commercial areas using the "People who bought this item also bought…" principle which is used heavily by business actors to influence customers. In a similar way, we can use the "people who adopted this system feature also adopted…" to make potentially personalized suggestion and positively influence individuals' behavior.
- Including official existing health records may also be extremely useful. First, this would feed the DT system with important information to take into consideration while providing feedback to the real twin. This would help in avoiding injuries by providing feedback that is tailored to people's health condition.

- Standards also exist for health records and it is of great importance to integrate them when including data from health records in our system in the future. This will help in leveraging more sources of data seamlessly.

8.2. Improve Data Analytics

- More data may help our existing algorithms be more efficient in their feedback computation process. New algorithms may be integrated to improve information extraction process in our system. Deep learning is one of the appealing areas that has to be leveraged. For example. an interesting area of future work for our system is preventing fatigue during physical activity, by monitoring of the heart rate and other metrics of the real twin and integrating fatigue prevention algorithms into the system. This would be taken into consideration while motivating the real twin to perform physical activity and would result in stopping all persuasion/motivation in order to prevent the individual from over working out. This is necessary as we are using different methods to motivate individuals to perform activity, and it is our observation during the experiments that many subjects were pushing themselves to donate more green energy for example.
- This is linked to another important area of future work in the physical well-being which is injury prevention. Since we are targeting a population of sedentary people who are just getting their body used to being active, it is our plan to adopt an injury prevention method and implement it within the system. This will help prevent injury not only when the fitness level is still low in the early stages of adopting a new exercise routine, but is also

encouraged as every level of fitness. Such prevention methods include establishing warm-ups, stretching and exercises commonly used by physiologists to this effect. The digital twin system can control through activity recognition that the real twin is indeed following the system recommendations and consequently display encouraging visual feedback.

8.3. Improve Interaction between Real Twin and Digital Twin

- Visualization of data and extracted information is certainly one of the aspects that could benefit the proposed system when leveraged at its best. Indeed, it is our aim to ultimately let the real twin be accompanied by a digital twin anywhere and anytime, as chosen by the real twin. The digital twin can then make him aware of the impact of his choices on his health and well-being, and provide recommendations at the right time to let him benefit from opportunities as they unfold, and provide him with the needed reminders about his goals as the real twin progresses through his daily activities. The feedback system may be improved to leverage the technological advances in the area of real-virtual world interactions. The individuals' engagement that happens while interacting with the virtual world could contribute to a better understanding of how daily choices affect their bodies, for example by offering to the real twin a virtual tour into the representation of their body provided by their digital twin.

- Furthermore, the digital twin system framework makes it achievable to study the different aspects of health as a whole, including the physical, social and mental well-being. Once enough data in the three areas has been collected about the real twin, it is then possible to study the effect of each aspect of health on the two other aspects and clearly see the connection between them. In addition to this, and most importantly, the visualization offered by the digital twin can make the real twin aware of those connections, and get the real twin to make better health choices by gaining as much knowledge as necessary for action.

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