FES SYSTEM FOR GAIT REHABILITATION OF PEOPLE WITH SPINAL CORD INJURY

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TRABALHO DE CONCLUSÃO DE CURSO EM ENGENHARIA ELÉTRICA
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FES SYSTEM FOR GAIT REHABILITATION IN SPINAL CORD INJURED PATIENTS

SISTEMA FES PARA REABILITAÇÃO DA MARCHA EM PACIENTES COM LESÃO MEDULAR

RAPHAEL BRACCIALLI DE LOYOLA

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TRABALHO DE CONCLUSÃO DE CURSO SUBMETIDA AO DEPARTAMENTO DE ENGENHARIA ELÉTRICA DA FACULDADE DE TECNOLOGIA DA UNIVERSIDADE DE BRASÍLIA COMO PARTE DOS REQUISITOS NECESSÁRIOS PARA A OBTENÇÃO DO GRAU DE ENGENHEIRO ELETRICISTA.

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RESUMO

Título: SISTEMA FES PARA REABILITAÇÃO DA MARCHA EM PACIENTES COM LESÃO MEDULAR
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Orientador: Prof. Antônio Padilha Lanari Bó

A lesão medular é um trauma gravemente incapacitante que provoca perda de funções sensitivas e motoras, comprometendo a mobilidade e a autonomia dos pacientes. Este trabalho revisa as tecnologias existentes para o monitoramento da marcha e estimulação elétrica funcional (FES) para a reabilitação da caminhada de pessoas com lesão medular. Propõe-se um protocolo adaptado para a atuação do ângulo do joelho baseado no sistema de ciclismo assistido por FES criado pela equipe de EMA [1], a ser associado à órtese ativa, andador e/ou suspensão corporal. Uma nova interpretação para as fases da marcha é apresentada como um algoritmo de detecção de fases para marcha patológicas, visando um conjunto exagerado, porém funcional, de movimentos das pernas. Testes offline foram realizados para avaliar o monitor de marcha apresentaram precisão de 58% a 90% de ciclos de marcha detectados. Testes qualitativos utilizando estimulação elétrica sensitiva indicam que a ativação muscular proposta por fase pode causar uma marcha funcional com maiores níveis de corrente.

Palavras chave: eletroestimulação, marcha, lesão medular, reabilitação.

ABSTRACT

Title: FES SYSTEM FOR GAIT REHABILITATION IN SPINAL CORD INJURED PATIENTS
Author: Raphael Braccialli de Loyola
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Spinal cord injury is a severely disabling trauma that causes loss of sensitive and motor functions, compromising patients mobility ant autonomy. This work reviews the existing technologies for gait monitoring and functional electrical stimulation (FES) for walk rehabilitation of people with spinal cord injury. It proposes a adapted protocol for knee angle actuation based on the FES assisted cycling system by EMA team [1], to be associated to active orthosis, walker and/or body suspension setup. A new interpretation for gait phases is presented as a phase detection algorithm for pathological gait dynamics, aiming for an exaggerated yet functional set of leg movements. Offline tests were conducted to evaluate the gait monitor and showed with accuracy from 58% to 90%. Qualitative tests using sensitive electrical stimulation cues indicate that the muscle activation proposed by phase may cause a functional gait with higher current levels.

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SYMBOLS LIST

Angles

θrt	Right Thigh Angle
θlt	Left Thigh Angle
θrs	Right Shank Angle
θls	Left Shank Angle
θrk	Right Knee Angle
θlk	Left Knee Angle

Thresholds

T_{thresh}	Thigh Threshold Angle
K_{thresh}	Knee Threshold Angle

1 INTRODUCTION

This chapter aims to bring the proposed research into context. It contains a brief explanation of what is spinal cord injury and how it affects committed patients, as the techniques that are commonly used for assistance in daily tasks, their pros and cons.

1.1 CONTEXTUALIZATION

According to the World Health Organization, up to five hundred thousand people suffer from spinal cord injury (SCI) every year [4]. The trauma often leads to severe impairment, loss of mobility and autonomy. There is a number of factors that might compromise neural pathways within the spinal cord and lead to a SCI. They can be classified as non-traumatic (NTSCI) or traumatic (TSCI) causes [5].

Non-Traumatic SCI are less common and include pathologies that affect the spinal cord directly such as tumors, infections and autoimmune diseases, or indirectly, such as hernias, osteoporosis, and others [6][7]. Causes are mostly correlated with age group, showing an increased incidence among the elderly [8].

The most frequent, TSCI regards physical stress on the spinal cord, caused by mechanical compression or extension, laceration or heat (observed in gunshot wounds), compromising the neural pathways. The most common causes are falls, vehicle accidents, violence and sports, and vary according to region, age group and gender [8]. Falls are the most common cause of TSCI among elderly people and vehicle accidents lead the causes among young people. Injuries related to violence are strongly correlated to country development. There is a predominance of males in all cases [9]. Traumatic SCI is estimated to be high as 23 cases per million, worldwide [10]. Mortality indexes following TSCI varies according to region development and can reach up to 22% [5].

1.2 PROBLEM DEFINITION

Long-term exercise training has shown to have great impact in different aspects of SCI patients health [11]. The most common and mandatory exercises on rehabilitation and health care for people with SCI are passive manipulation exercises [12]. It consists in a therapist performing certain movements on the limbs to slow down the natural decay of bone density, minimize muscle atrophy, improve blood flow and consequently skin health. Even though very basic and essential, its benefits are limited, as it poorly mimics the natural mechanical and physiological stimulus healthy people are submitted to.

An enhanced alternative technique exploits functional electrical stimulation (FES), used in clinical and rehabilitation environments. It consists in electrical current pulses with controlled parameters applied to either muscles or nerves to induce artificial muscle contraction. Active exercises provide augmented benefits when compared to passive limb manipulation [13]. It requires an specific set of hardware and therapist supervision. The technique presents some limitations regarding the control and strength of the elicited movement, specially when subjected to a load such as the body weight. Also, some muscle groups are deep under layers of adipose tissue, making it very difficult to stimulate using surface electrodes.

Either active or passive, the above techniques do not apply significant mechanical load over bone and joints when compared to body weight, and are limited to a sitting or lying position, which also limits benefits of the exercise. Verticalization techniques are also commonly found and concern the usage of tilt tables, walkers or passive orthosis for helping a SCI patient in the upright position. These techniques are known to improve not only the decay of bone density, but spasticity, bowl and bladder function, as general well being [14][15].

1.3 PROJECT OBJECTIVES

Allowing people with SCI to overcome everyday obstacles presented by loss of mobility poses a challenge for both the health and engineering communities. The project aims to create a superficial FES assisted gait system to be later integrated to either a body suspension and treadmill setup (BSTS) or active orthosis (AO).

The analysis aims for the sagittal plane. Two main muscle groups of each leg will be targeted by the system, hamstrings and quadriceps. They are the main responsible for knee dynamics and body support throughout the gait, and can be easily accessed by superficial FES, allowing a non invasive protocol.

Calves and tibialis anterior act on the ankle angle on the sagittal plane, causing feet extension and flexion, respectively. Stimulation for theses muscle groups can be later on integrated to the system, but in this work they are not considered.

Therefore, the main goal is developing a reliable gait event detection system that relates muscle activity of quadriceps and hamstrings to knee dynamics during a functional gait.

Specific goals include:

- Reviewing other research and the state of the art for FES assisted gait, SCI ambulation and gait monitoring;
- Quantitative testing of event detection accuracy;
- Qualitative testing of muscle group activation throughout the gait;

1.4 MANUSCRIPT ORGANIZATION

The manuscript is divided in chapters and sections as to provide a better understanding of the system conceiving and development. In Chapter 2 the reader will find a literature review of basic concepts of anatomy and physiology of the nervous system, concepts of electrical stimulation, as some references to recent research developed in the field over the years. Once concepts and state of art are presented, Chapter 3 describes step by step the experimental setup, the approach on defining a new set of gait phases and building a finite state machine that will allow the system to actuate. Chapter 4 shows simulation results with graphical visualization and data analysis. It also describes the qualitative experimentation performed using the system with functional electrical stimulation and a passive orthotsis. Finally, Chapter 5 offers a discussion of the quantitative and qualitative results obtained in the previous chapter. It also presents a series of possible improvements that could be implemented to different aspects of the system development, that could be starting points for future work.

2 LITERATURE REVIEW

In this chapter the goal is to describe anatomical and physiological concepts and other research that have been done in the context of gait pattern recognition, leg muscle activity, FES applications and FES assisted gait systems.

2.1 NERVOUS SYSTEM

The nervous system is a structured network of cells concerns mainly the exchange and processing of information throughout the body. This information is transmitted in form of electrical impulses by the constant re-polarization and intercommunication of special cells called *neurons* [16].

The nervous system can be divided in two different scopes, physiologically and anatomically.

Physiologically, it can be classified either as somatic (SNS) or autonomic (ANS) nervous system. Each is present in both the central and peripheral nervous systems, but carry out very different functions. The SNS includes sensory neurons receptors and pathways for skin, muscles and joints, as motor neurons and its pathways. It is mostly related to stimuli we are conscious and/or have control over. In contrast, the ANS regards involuntary and unconscious stimuli and regulation. It can be divided as sympathetic and parasympathetic. The first causes blood vessels to constrict, heart hate increase and other effects of "fight or flight" response, as the second has opposite function and causes the body to enter a more relaxed "rest and digest" state. [17].

Anatomically, it can be divided in peripheral nervous system (PNS) and central nervous system (CNS). The PNS includes all peripheral pathways that reach and connect structures from the body back to the CNS. On the other hand, the CNS is enclosed by bone structures and comprehends both the brain and the spinal cord. It processes, receives, transmits information to the PNS regarding sensorial, motor and physiological functions. [18].

The spinal cord extends from the base of the skull all the way down through the spine, connecting to different pathways along the way, as shown in Figure 2.1. It is responsible for re-transmitting signals to and from the brain to the peripheral nervous system, as for some spinal reflexes. Spinal reflexes regard activation of neural response via reflex arcs pathways, allowing a faster response to stimuli [2].

2.1.1 Spinal Cord Injury

Spinal cord injury (SCI) is strongly disabling trauma in the central nervous system (CNS) that can even be fatal. It occurs with the commitment of neural pathways of the spinal cord, and often leads to severe mobility impairment and has great impact in the life of affected people [19].

The injury can be classified by completeness and level. As to completeness, it can be incomplete or complete [20]. In incomplete lesions there is partial preservation of sensory and/or motor function bellow the level of injury, whereas complete lesions do not present any neural response bellow injury. The level of injury regards the traumatized segment of the spinal cord. The injury may cause partial or total loss of motor control, sensibility and autonomic functions that correlate to the segments at and bellow the injury, as shown in Figure 2.1. As to functionality, we define paraplegia and tetraplegia as the SCI the compromises, respectively lower

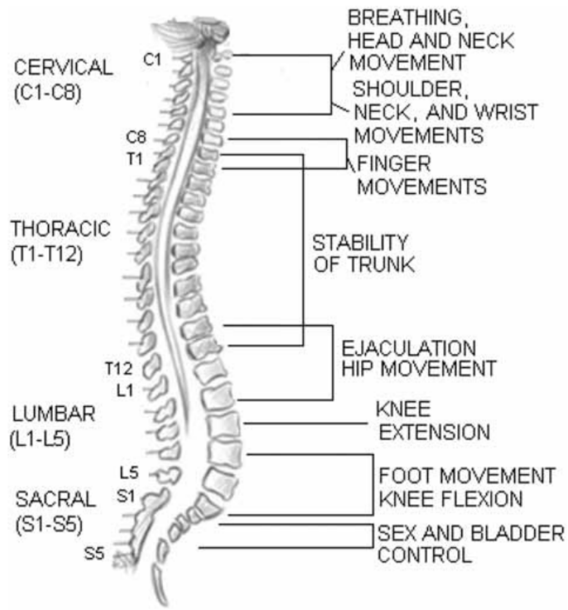

Figure 2.1: Spinal cord segments by function, according to Farina [2]

limbs and all limbs, both accompanied by some level of sensory/motor loss of the trunk.

SCI commonly leads to cardiovascular complications, loss of bladder and bowel control, temperature deregulation and sexual dysfunction [21]. The scenario can also be followed by psychological and socioeconomic consequences caused by the impairment, as daily tasks such self-care, commuting, and general accessibility might be hindered by the loss of mobility. All this factors might contribute to an aggravated depletion of autonomy, self esteem and life quality [22].

Several studies offer different approaches to try to restore motor and sensitive function to people afflicted by SCI. There is a large field of neurorestoratology (study of neural restoration), including mainly cell therapy and transplants that may bring some level of functional improvement, but there is still no definitive and effective cure for SCI [23].

In this context of impairment and rehabilitation, there are measures that can be taken regarding one's health and empowering. A series of mechanical adaptations come into the life of impaired people as to provide autonomy, facilitate access, put daily objects within their reach. As to health care, maintenance exercises and procedures are mandatory and are often confined to physiotherapy clinics, where a strict set of exercises aim to avoid atrophy, loss of bone density and ease consequences of compromised blood flow [24].

2.2 ELECTRICAL STIMULATION

Electrical stimulation (ES) technique regards electrical current applied to one's body with therapeutic purposes. The concept of ES dates from the 18th century, when Luigi Galvani first observed the occurrence of electricity in biological tissue, and how it was susceptible to external electrical charges [25]. Later, in the 19th century, Guillaume Duchenne was the first to ever apply electrical stimulation as a medical therapy successfully [25][26].

2.2.1 Functional Electrical Stimulation

Functional electrical stimulation is a technique that involves applying controlled electrical current to nerve fibers in order to activate either motoneurons or reflex mechanisms and cause muscle contraction [18]. It has been proven to ease some of the consequences of SCI, such as loss of bone density and muscle atrophy [27]. It also brings along cardiovascular benefits of physical exercises that would be impossible if unassisted, specially for people with quadriplegia [11]. Also, FES stimulates both efferent and afferent nerves, combining the benefits of the physical exercise with an improved CNS neural plasticity [2] [28].

Since the 1960's, FES has been studied at an increasing rate [25]. Research include several studies on FES parameters [29][30] and protocols [31][32] to better evoke muscle activity. A better muscle response relates to generated joint torque, movement cadence and delayed fatigue [33].

FES delivers electrical current via electrodes. They act as a voltage or current source as in a circuit where the stimulated area acts like the circuit load. Note that current controlled sources have better accuracy over the charge delivered to the patient, as impedance of electrodes themselves and of the biological structures involved may vary. When using multiple channels, they can all share a passive electrode that drains current (monopolar) or have individual passive electrodes (bipolar), the last being the more selective [18].

Electrodes can be either subcutaneous or surface electrodes. The first involves a much more invasive procedure and will not be treated or discussed in this work. Surface electrodes allow a non-invasive stimulation of nerves at the cost of a lower selectivity, but is still suitable for targeting simpler and larger muscle groups [2].

Finally, stimulation parameters include frequency, waveform, amplitude and pulse width. Frequency is the rate at which the signal repeats itself. Waveform denotes the function that describes the amplitude of the signal throughout a wave period and whether if it is unidirectional or bidirectional. Bidirectional recommended for lessening the potential damage to tissues. Amplitude is the highest value of current (or voltage) the signal reaches. Pulse width is the time of activation of the signal, often directly related to the delivered charge [18].

Nevertheless, FES has shown itself to be an effective rehabilitation technique, capable of developing physiological functions that would be otherwise severely compromised [33].

2.2.2 FES Applications

Another advantage of the technique is that it can be applied to different rehabilitation exercises, sports or daily tasks. With proper apparatus, supervision and stimulation protocol, it can be used tot rehabilitate and bring autonomy to impaired patients. Many FES applications protocols will increase engagement to the activity and social engagement. Some of the studied applications are cited bellow:

Transfer

For instance, a study used FES to aid SCI patients transfer from one sit to another. This task can be stressful for the wrists, elbows and shoulder joints and must be performed dozens of times daily, when driving or going to the toilet. In this study, quadriceps were stimulated to sustain some of the body load and ease the stress on the upper limbs while transferring sits. Lower limbs would take up to 30% of body weight during transfer [34].

Rowing

In the scope of sports, knee torque control has been used for allowing a more complete motion while rowing for SCI patients. People who would otherwise row using upper limbs only, assisted by this protocol, may perform a full range of motion including lower limbs, identical to what is observed in healthy athletes. That greatly increases physical and psychological involvement to the sport [35].

Cycling

Another application allows the impaired patient to practice a sport that otherwise would be impossible: cycling. Some studies have developed protocols and control strategies that coordinate leg muscle activation to generate the necessary torque to perform a cycling movement [1][36][37].

Walking

In a more rehabilitative scope, FES can be applied to lower libms in order to reproduce gait pattern, by stimulating different leg muscles in a ordered sequence. Studies on walk rehabilitation using FES are often integrated with body suspension [38] and/or orthosis [39] generally consist in either an time oriented stimulation or a gait event oriented stimulation. The first presents easier setup and simpler system. The second involves data collecting and has shown itself to be a superior approach, with better results [38]. Gait event oriented stimulation regards both identifying gait phases in real time and actuating via electrical stimulation. Electrical stimulation may be similar from technique to technique, but the identification of gait phases within a cycle, specially in pathological gaits, can be a challenge [40] [41].

2.3 GAIT DESCRIPTION

The term *gait* denotes a sequence of movements and cadence of one's act of walking. Gait phases are sections of the cyclic movement divided by gait events. There are different methodologies to detect gait dynamics, most including either force sensors [42] or inertial measurement units (IMU) attached either to patients feet [40] and/or legs [43] in order to detect gait events. Gait phases of interest may vary depending on the pattern of actuation and muscle groups that are targeted.

The use of finite state machines (FSM) has proven to be an effective tool for supervisory control when detecting gait phases, allowing a switched and more robust control [44]. The gait it self can be represented as a state machine, where gait events trigger transitions between phases [3]. These events must be detectable with the input data [43][44] with little or no delay, for real time detection. By observing this events correctly it is possible differentiate the current gait phase any given moment.

The literature [3] commonly describes the gait as a cycle divided in two phases: *stance phase*, when the observed leg has contact with the ground and support partially or fully the individual body weight; *swing phase* occurs when the leg leaves the ground and moves forward until it touches the ground again. Each phase can also be divided in smaller periods, as shown bellow. Figure 2.2 shows a full gait cycle observed by the right leg.

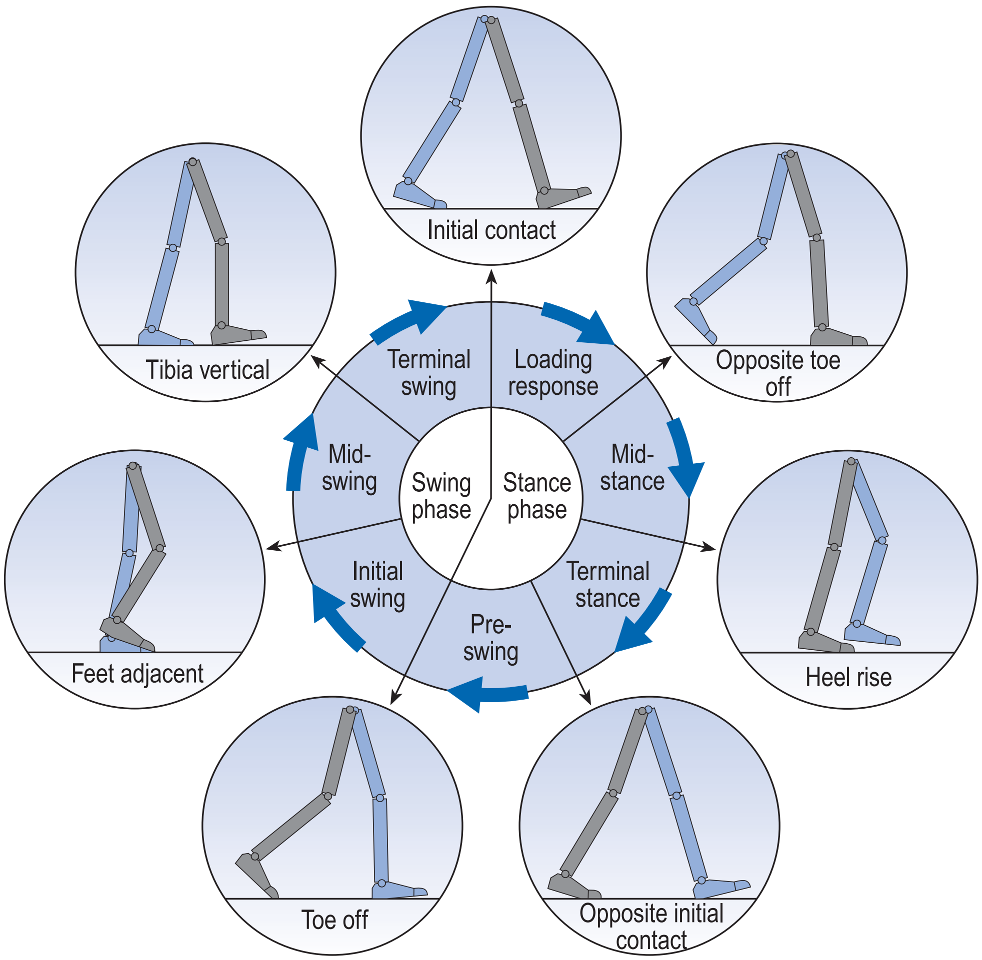

Figure 2.2: A full gait cycle for the right leg (in grey), adopted from Whittle [3]

2.3.1 STANCE PHASE

The following components are defined within the stance phase:

• **Loading Response:** starts with the heel strike event, defined by the initial contact of a given foot with the ground. During this phase, the leg gradually takes over the body weight.

• **Midstance:** when opposite toe off event occurs, the leg has taken over all body weight and hip extension pulls the body forward.

• **Terminal Stance:** while still extending the hip, this phase starts at give leg heel rise and finishes the opposite foot touches the ground.

• **Pre-swing:** from the moment of opposite initial contact up until toe off, this phase corresponds to the loading response of the opposite leg.

2.3.2 SWING PHASE

The following components are defined within the swing phase:

• **Initial Swing:** first phase of swing, from the moment the toes come off until the leg is leading.

• **Mid-swing:** from the moment the given leg is leading up until the tibia vertical event, when lower leg is orthogonal to the gait plane.

• **Terminal Swing:** last phase of swing. Knee extension takes place projecting the foot further in front until initial contact.

2.4 FES WALKING - STATE OF THE ART

This section presents the research of the state of the art for gait event oriented FES walking systems. Research of the state of the art included searches using the platform *Google Scholar (www.scholar.google.com)*. For this purpose, key research terms were chosen as: *fes walking*, *electrical stimulation walking*, *fes gait* and *gait spinal cord injury*. Time range included the last eighteen years, from 2000 to November 2018. In the first scan, first 20 results were considered for each research term, ordered by the platform's *Sort by relevance* option. Results were considered by title accordance to the theme, selecting 33 out of the 80 previous results. Second scan included abstract reading and evaluation of work's relevance, selecting 9 results. Third scan consisted in full article reading and did not exclude any works. Results are shown in Table 2.1.

Input data collection varies with application, but portable systems mainly consider accelerometers, gyros and force sensitive resistors, which are all low-power consumption devices with reliable data accuracy. All considered works adopt somehow the use of finite state machines. Some go further and implement control logic within the identified states. Actuation mostly include muscle groups responsible for joint dynamics of hip, knee and ankle. Knee angle control is present in most systems, which denotes it's importance for gait dynamics.

In 2001, Pappas et al [44] have proposed a robust gait detection system using gyroscopes and force sensors and with accuracy of 96% in impaired gaits. Force sensors were mainly responsible for defining gait phases,

Table 2.1: Research results of research on the terms *fes walking*, *electrical stimulation walking*, *fes gait* and *gait spinal cord injury* from 2000 to November 2018.

Year	Sensor Type	Logic Characteristics	Actuation	Reference
2001	gyro and fsr	fsm and ml	none	[44]
2001	fsr	fsm and fuzzy	varies	[45]
2004	fsr and gyro	fsm and ml	ankle flexion or flexion reflex	[46]
2008	acc and gyro	fsm and kalman prediction	flexion reflex	[47]
2009	pot	fsm	ankle, knee, hip and trunk	[48]
2011	encoder	fsm and fuzzy	knee extension and spring break	[49]
2014	pot, fsr and torque sensor	fsm, pid and ml	passive elastic, knee	[50]
2016	encoder	fsm torque control	knee and motors	[51]

Acronyms: acc: accelerometer; gyro: gyroscope; fsr: force sensitive resistor; pot: potentiometer; fsm: finite state machine; ml: machine learning; fuzzy: fuzzy logic. Joints names regard electrical stimulation of muscle groups related to that single sagittal degree of freedom in both directions, when not otherwise specified differently.

and most interestingly, resetting gyroscope offset during stance phase in order to avoid unwanted orientation data drift. Note that the system, even though meant for FES integration, did not include any actuation yet. Also, all impaired subjects had some level of lower limbs control that allowed them to perform short distance gait.

In the same year, Skelly et al [45] developed a real-time method for gait event detection while using FES. It consisted in a two-level algorithm. The lower level, a *a fuzzy logic* algorithm classifies data of insole force sensitive resistors in gait phases. Classification is then reviewed by a upper level supervisory controller. An advantage of the technique regards the training of the classifier for each leg of each subject, providing a customized identification rule bases. Tests were performed in three subjects with different levels of impairment and different muscle stimulation, but were described as successful, easy setup and cosmetically acceptable.

In 2004, Pappas et al [46] describes a gait phase detection sensor set used with FES. In contrast to the work developed back in 2001, the system now also differentiates weight shift of standing and actual walking. It still uses insole force sensors and gyroscope to detect events and transition a state machine. Here, event detection only triggers a preprogrammed stimulation sequence for each phase, but it suggest the development of closed-loop controllers within states. The use of inertial sensors allow not only a classification of gait phases, but further analysis of gait patterns. Again, tests were performed on two subjects with incomplete SCI and unilateral paralysis. The paper does not present accuracy results for the detection, but describes positive feedback from subjects, and comments that the $70ms$ delay for the detection system was sufficiently small.

Cikajlo et al [47], in 2008, offers an algorithm for estimating shank orientation and velocity with dual-axial accelerometers and a gyroscope, using a Kalman filter [52]. It discusses filtering techniques for raw sensor data and mathematical algorithms for control. Orientation data was validated by comparison to an optical motion analysis system, and was described as reliable and efficient.

In 2009, Kobetic et al [48] explore the feasibility of an active orthosis and FES system for lower limbs. A hibrid neuroprosthesis, as it is called, combines gait phase detection and muscle stimulation with hydraulic rotatory actuators placed on orthosis joints that will complement the muscle torque in order to develop a functional gait pattern. Again, predetermined stimulation patterns are triggered within states of a finite state machine, for which transitions rely on force sensitive sensors and optical switches found on the orthosis. Tests were performed on two nondisabled subjects and SCI subject with multichannel implanted electrodes. Nondisabled tests did not include electrical stimulation and aimed for mechanical features mostly. The SCI subject had

FES actuation on trunk, hips, knees and ankle joints. The system was descried to successfully generate gait, stand and stair climbing movements by supporting the body locking joints during stance phase, and not opposing movement generated by FES when on swing phase. Although feasible and practical, it still was not cosmetically acceptable and easy setup, as not all components were designed for the purpose of this work.

Later, in 2011, Jailani et al [49] proposed the implementation of a finite state controller for a hybrid orthosis technique with springs and joint breaks that would facilitate the control of knee angle. Springs placed over the hamstrings would act on knee flexion, while hamstrings were stimulated with FES and used for knee angle control. The work focuses on the swing phase of the gait and considers the natural hip flexion that results from knee flexion as enough for performing the swing of the leg. Simulation results showed improvement of knee and hip trajectories due the finite state controller.

Ama et al, in 2014, offered a cooperative control strategy for FES-robot hybrid knee-ankle-foot neuroprosthesis. The system aims not only to identify gait phases, but also evaluate movement dynamics, identify muscle fatigue and balance power contribution of exoskeleton and muscles. Only muscles responsible for knee dynamics were stimulated with superficial FES and actively controlled, and ankle was equipped with a passive elastic actuator. Force sensitive resistors and potentiometeres allowed a finite state machine identify and transition gait phases, while torque sensors could identify muscle strength and adapt electrical motors actuation. Tests performed in four nondisabled volunteers were reported as safe and comfortable, and the system could successfully balance FES and robotic actuation while inducing locomotor activity. Superficial stimulation also offers a much easier setup and less invasive approach.

The last work reviewed was developed by Ha et al in 2016 and also focuses on cooperative control between FES and motors. It consists in an active orthosis and FES setup that actuates on hips and knee angles by using motors, hamstrings and quadriceps stimulation. It presents two control loops, one for motors for trajectory control, and one for muscles, that calculate stimumlation levels based on torque profile of the previous step. Cooperative control strategies are good solutions as they allow a adjustable rehabilitation intensity throughout a session or treatment, and bring functionality to the gait task.

2.5 COMMERCIAL APPLICATIONS

This section describes some of the commercial FES, ambulation and monitoring technologies developed for gait rehabilitation available in the market at the time of research. They are meant for rehabilitation clinics and research, to be operated by professionals, and offer a range of friendly user interface capabilities.

2.5.1 Hasomed RehaGait

The *Hasomed RehaGait* is a portable wearable gait monitoring system. It consists in a set of seven inertial sensors to be attached to feed, shanks, thighs and hip. It allows therapists to identify gait phases real time and evaluate key aspects of body dynamics during the walk. Its been validated by studies as a reliable tool for gait monotiring, specially in level [53][54]. The system can be seen in figure 2.3.

Figure 2.3: *Hasomed RehaGait* gait monitoring system.

Figure 2.4: *Hasomed RehaStim2* electrical stimulation device.

2.5.2 Hasomed RehaStim2

The *Hasomed RehaStim2* is an electrical stimulation device for rehabilitation. It is the following version of the device used the work shown in the following chapters. Among other modes and applications, it includes a The *Sequence Mode* that allows therapist to time stimulation levels and channels as to develop a sequence of movements to perform a specific task, such as walking. The device, in version 2, supports interfacing with the *Reck MOTOmed* pedal, but not with other gait monitoring devices (not even The *Hasomed RehaGait*), so it operates as an open-loop system. The *Hasomed RehaStim2* can be seen in figure 2.4.

2.5.3 Hocoma Erigo

The *Hocoma Erigo* is a system developed for early rehabilitation stages of the gait. It combines verticalization of a tilt table with FES and robotic leg movements, and aims for the therapeutical benefits of active exercises previously discussed [55]. The system setup can be seen in figure 2.5

2.5.4 Hocoma Lokomat

The *Hocoma Lokomat* concerns a complete ambulation system including treadmill, body weight support, active orthosis and feedback interfacing and gamification. *Hocoma* manufecturer describes it as a middle stage rehabilitation system. It can be seen in figure 2.6

Figure 2.5: *Hocoma Erigo* early gait rehabilitation system.

Figure 2.6: *Hocoma Lokomat* middle stage gait rehabilitation treadmill, orthosis and body weight support.

2.5.5 Hocoma Andago

The *Hocoma Andago* is robotic body weight support that follows and aids locomotion while detecting movement intentions. It is presented by the company as the last stage of rehabilitation before independent gait, but it does not integrate electrical stimulation, not being suitable for complete spinal cord injuries. The system can be seen in figure 2.7.

Figure 2.7: *Hocoma Andago* last stage gait rehabilitation robotic body weight support.

3 METHODOLOGY

In this chapter are presented methods and materials used to develop the new supervisory control for the FES assisted gait system.

3.1 INTRODUCTION

The system aims to assist or cause gait-like lower limbs muscle activation. To do so, it must both identify current gait phase and actuate on leg muscles. The FES assisted gait protocol is based on an existing FES cycling system by the EMA team, at the University of Brasilia [1]. It uses the same hardware with extra stimulation channels and electrodes, and software with with extra data input and output. The control node will be re-designed to run while receiving data from four IMU, instead of only one. Also, it will send out electrical stimulation parameters to the stimulator API. The supervisory controller consists in a FSM and aims to stimulate knee flexors and extensors as to allow an exaggerated yet functional leg dynamics throughout the gait.

3.2 MATERIALS

In order to close the control loop of the system, the system require both actuation and data acquisition. Actuation on the muscle, as explained previously, can be done by applying regulated electrical current to neural pathways, causing muscle activation and joint torque. Orientation feedback is possible due inertial motion sensors placed on the leg. A PC receives data, processes and send out stimulation commands. The complete setup can be seen in figure 3.1.

3.2.1 Inertial Sensors

Inertial measurement sensors are used for acquiring orientation data from the limbs of the subject. The IMU used for this purpose is the *3-Space Sensor*, from *Yost Labs*. Each sensor is composed by three main electronic circuits: gyroscope, accelerometer and magnetometer. Each measure, respectively, angular velocity, linear acceleration and magnetic field orientation. Composition and computation of these measures provide absolute orientation data.

For this purpose, four sensors were used. They can connect to the system via a wireless USB hub or direct USB connection. When operating wireless, setup becomes easier, but it comes at the price of a short battery life and low data rate, up to $15Hz$. When wired, sensors will power via USB and data rates go up to $60Hz$. Limitations maybe related to software implementation.

Existing on board signal processing waives the need for the development of filters in the system. It allows a series of requests for different data types. In this work, quaternions were used, in order to exclude discontinuity in measurement, that can be easily converted later on to euler angles for a simpler and intuitive parameter calibration.

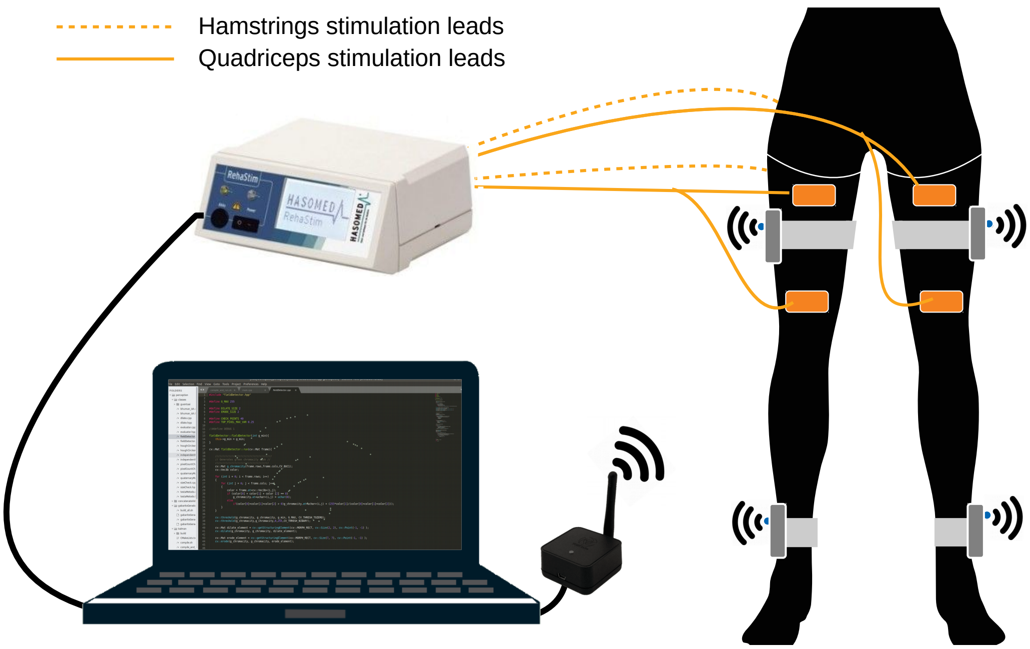

Figure 3.1: Complete setup, including computer, stimulator, electrodes, wireless hub and intertial sensors.

Figure 3.2: The IMU wireless sensor and a wireless dongle (receiver) *3-Space Sensor*, from *Yost Labs*.

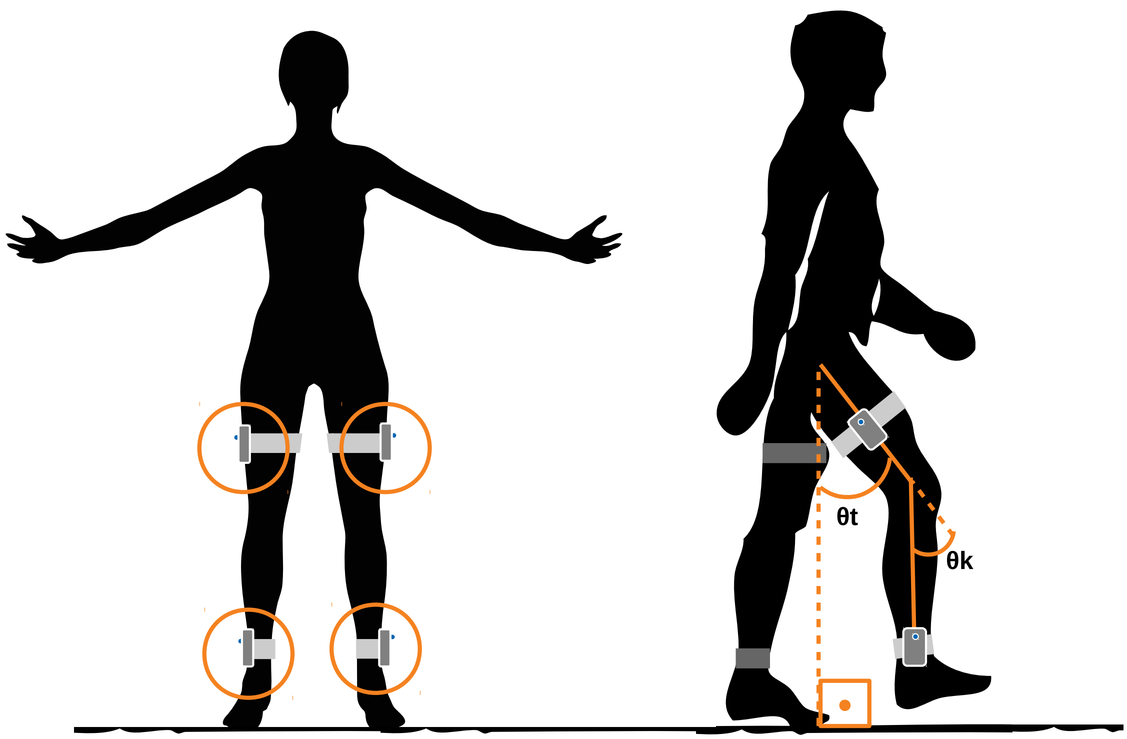

Figure 3.3: IMU sensors positioning.

Dimensions	*13,5cm x 15cm x 7cm*
Input	*110-240VAC 50-60Hz max. 150W*
Battery	*2700mAh*
Channels	*8*
Max. output voltage per channel	*154V*
Current output per channel	*2 to 130mA in steps of 2mA*
Waveform type	Biphasic, charged balanced
Stimulation frequency	*10 to 50Hz in steps of 10Hz*

Table 3.1: *Hasomed RehaStim* stimulator specification.

Figure 3.4: The electrical stimulation device $RehaStim$ from $Hasomed$ and a set of surface electrodes.

3.2.2 Stimulator

The stimulator used to elicit muscle contraction is the *RehaStim*, from *Hasomed*. It is a 8-channels portable electrical stimulation device that operates within specifications showed in table 3.1. The device specifications cover all FES parameters to be introduced.

The $RehaStim$ stimulator delivers current through a pair of cables and 5x10cm electrodes, by channel. It has two main operation modes: Science Mode and Current Test. The first allows the communication port to receive messages from the API running in the computer, while the second is used for manual parameters setup and can be used in the calibration stage. The device and electrodes can be seen in figure 3.4.

3.2.3 Computer

A computer must be used to link hardware and process data. Two different setups were used for distinct situations, a notebook for developing and testing the system, and an embedded computer for data collection.

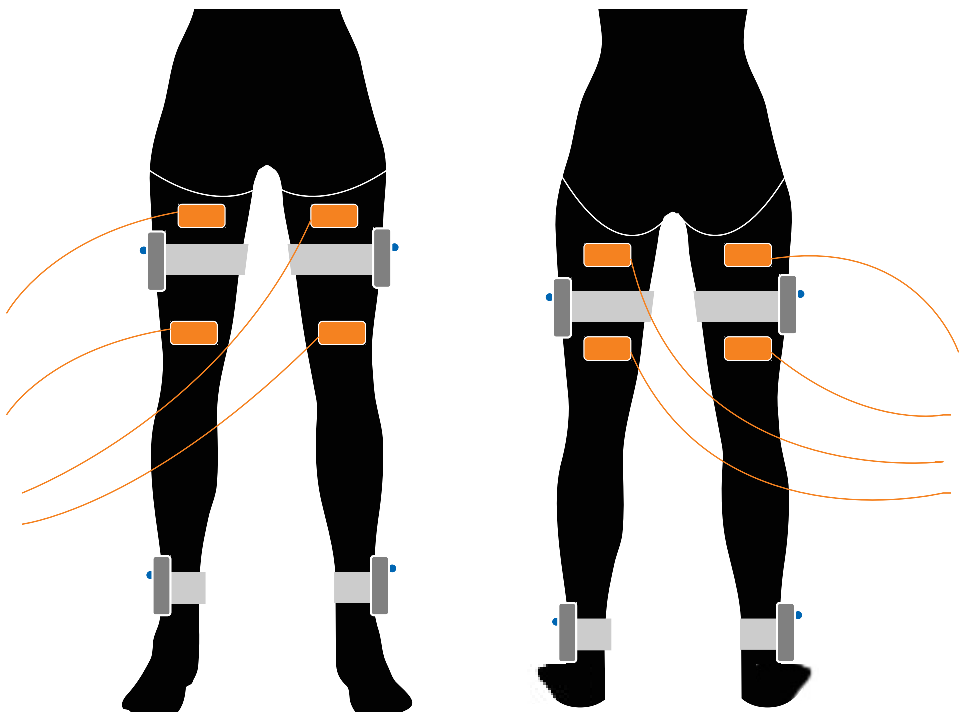

Figure 3.5: The electrodes are positioned on the upper and lower portions of quadriceps (left) and hamstrings (right), allowing the electrical current to flow through the muscle group.

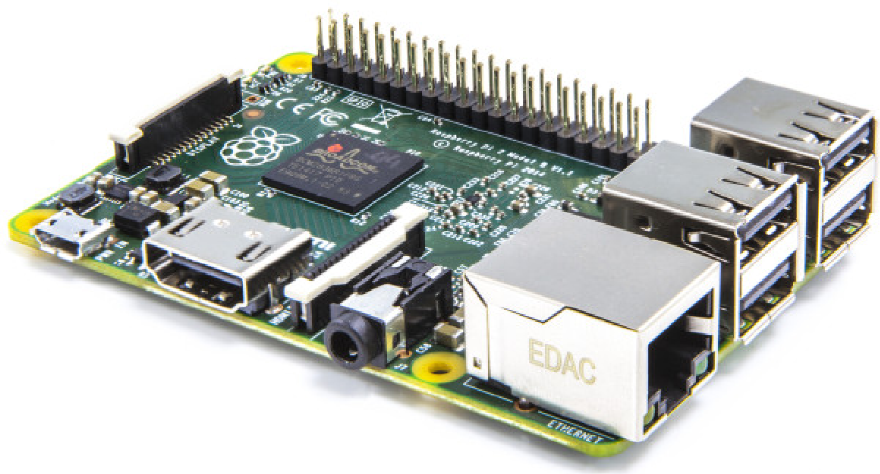

Figure 3.6: Raspberry Pi 2 Model B.

3.2.3.1 Notebook

It consists in a simple $2.4GHz$ quad core processor with $4GB$ of RAM and $256GB$ storage HD. Operational system used was a Linux distribution, Ubuntu 14.04 LTS, and the software was based on the ROS (Robotic Operating System) framework. It connect to the IMU wireless hub and to the electrical stimulation device via USB ports. No graphical interface was developed, so all commands must be entered via command line. The ROS environment also allows a simple data visualization, used for debugging.

3.2.3.2 Embedded Computer

The sampling rate using the IMU wireless hub could not be improved. Reasons may be hardware or software. In order to facilitate data acquisition at a faster rate and avoid cables, an embedded computer was used. It consists in a *Raspberry Pi 2 Model B*, $900MHz$ quad core processor with $1GB$ of RAM and a $32GB$ storage SD card 3.6. It provides 4 USB ports that allows connecting the four IMU at once using the wired protocol. The *Raspberry* connects to a WI-FI network along with the notebook where commands are sent via *secure shell protocol* (SSH). It can be easily powerd by a portable $5V$ cellphone charger.

3.2.3.3 ROS

The framework Robotic Operating System was used to nest all of the software used for data collecting, processing and transmitting. It is mainly composed by nodes and topics. The first regard software scripts, including specific libraries, and are responsible for computing data and executing tasks. The second are communication channels created by nodes so they can publish and receive data of predefined types. Packages are abstraction of modules that group nodes within a project. Additionally, ROS offers several package tools for generating real time graphics, diagrams, saving time-stamped data and debug tools.

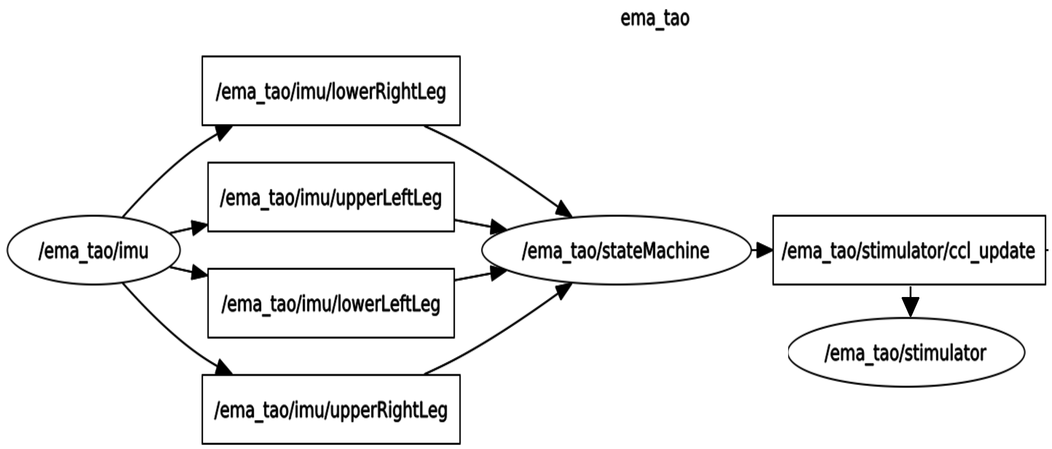

Figure 3.7: Diagram generated by the ROS tool *rqt_graph*. It shows all running nodes and topics.

3.2.4 Software Architecture

The software architecture is based in the ROS framework, with nodes for each of the main parallel tasks of the system. The nodes are:

• The **imu** node contains the API that communicates with the IMU dongle and receives inertial data. It is responsible for choosing, setting up and calibrating the sensors, then making data available via topics **lowerRightLeg**, **upperRightLeg**, **lowerLeftLeg** and **upperLeftLeg**.

• The **stateMachine** node receives data from the **imu** node. It publishes stimulation parameters in **ccl_update** topic for the **stimulator** node. It is responsible for processing inertial data, calculating current machine state and sending out FES parameters. It contains data conversion scripts from quaternion to euler angles used for triggering FSM transitions.

• The **stimulator** node reads data packages published by the control node and updates the stimulator manufacturer's API, wich communicates to the stimulation device itself.

A software diagram can be observed in figure 3.7. It was generated by the graphical ROS tool *rqt_graph* and shows all current running nodes and topics and how they correlate. Note that ellipses represent nodes, as rectangles represent topics. Also, the common path *ema_tao* refers to the package containing all topics and nodes.

3.3 GAIT PHASES

3.3.1 Defining Gait Phases

The first assumption is that the events defined by literature [3] are not always directly related to muscle activity and knee dynamics, but mostly to feet contact and support. When dealing with pathological gaits,

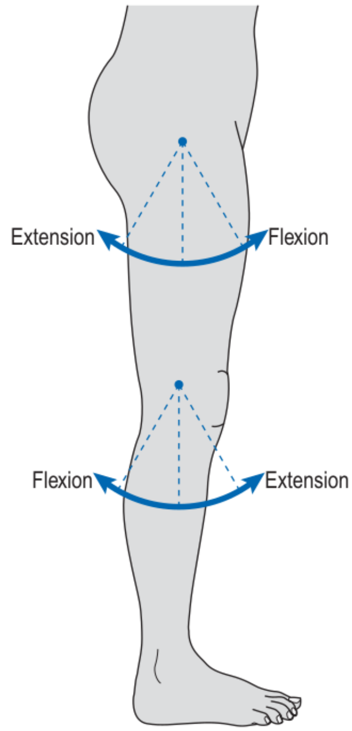

Figure 3.8: Movement about hip and knee joints in sagittal plane, adopted from Whittle [3].

which is the goal of the system in question, some of the phases, periods and events will most likely not apply [56]. A SCI patient in rehabilitation will probably experience partial to total leak of muscle control and, even aided by FES, muscle weakness due atrophy. Therefore, the need for a new set of states that aim to describe gait that is functional, even though it may not account for the same features observed in a healthy one.

A robust set of states also rely events that can be easily detected, even in a pathological gait. The new events are based in simple orientation features observed in a functional (not necessarily healthy) gait, that can be achieved with aid of therapist manipulation or active orthosis. This way, phase transition will only occur when full motion is completed.

The control of knee angle was chosen as primary goal because of its importance during the gait and the effectiveness of superficial FES on the responsible muscle groups, which are quadriceps and hamstrings. The quadriceps are responsible for knee extension as the hamstrings cause the knee to flex, as in Figure 3.8.

Since knee angle is a relative measurement between thigh and shank, those two portions of the leg will be attached to IMU so orientation thresholds can be defined as events to transition states of the FSM and, in the future, allow some other control strategies within each state.

While developing the supervisory controller, online tests were conducted while using the graphical command tool *$ rqt_plot* available in ROS. It allowed to visualize orientation features of both thighs and shanks throughout the gait and build the FSM by defining its states, events, transitions and interest data input. Three distinct knee behaviours were used to define states and their actuation: flexion, mostly during swing phase; extension, at the end of swing phase when leg reaches forward; and rigidity, to resist the bending torque that is

Table 3.2: Gait description by proposed state.

State	Right Leg	Left Leg
0	Knee flexion and forward	Knee extension and backwards
1	Knee extension and forwards	Knee extension and backwards
2	Knee resists load and backwards	Knee extension and backward
3	Knee extension and backward	Knee flexion and forward
4	Knee extension and backward	Knee extension and forwards
5	Knee extension and backward	Knee resists load and backwards

Table 3.3: A time-line comparison between the gait cycle and the proposed states. Note that each proposed state define behavior of both legs.

<table>
<tr><th>State</th><th>Right Leg</th><th>Left Leg</th></tr>
<tr><td rowspan="2">2</td><td>Loading Response</td><td>Pre-Swing</td></tr>
<tr><td>Midstance</td><td>Initial Swing</td></tr>
<tr><td>3</td><td rowspan="2">Terminal Stance</td><td>Mid-Swing</td></tr>
<tr><td>4</td><td>Terminal Swing</td></tr>
<tr><td rowspan="2">5</td><td>Pre-Swing</td><td>Loading Response</td></tr>
<tr><td>Initial Swing</td><td>Midstance</td></tr>
<tr><td>0</td><td>Mid-Swing</td><td rowspan="2">Terminal Stance</td></tr>
<tr><td>1</td><td>Terminal Swing</td></tr>
</table>

generated by the patients body weight during most of the stance phase. Note that the behaviour is not always contained within one of the reviewed literature gait phases, reinforcing the usage of a new description.

3.3.2 Proposed Gait Phases

The data analysis resulted in a set of six gait phases and six transitions. Each phase defines the knee behaviour during the gait in both leg and relates it to a combination of active muscle groups that are expected to cause that specific behaviour. The definition of both legs behavior within a single states intends to reinforce the sequence of steps and movements. The normal dynamic that was observed in the gait of healthy subjects is shown if Table 3.2. Additionally, a time-line comparison between traditional and proposed phases can be seen in Table 3.3. Note that, aiming to to build a FSM that will send out stimulation commands for both legs, each phase accounts for a single combination of knee behaviours and, when compared to the traditional gait analysis, often splits and/or groups phases. Also, states will then be related to stimulation parameters that reinforce the expected knee dynamics. Nevertheless, it is also possible to see similarities, as some transitions will happen at the same time in both gait propositions.

3.4 FINITE STATE MACHINE

A FSM is an abstraction that consists of a finite number of states, events and transitions. States will define the system current characteristics and how to actuate or control it. Events are measured features within the system that signal inputs that trigger transitions between states [57].

Table 3.4: Transition matrix for the FSM. The structure will base improvements with addition of more transitions.

State	$\theta rt > T_{thresh}$	$\theta rk < K_{thresh}$	$\theta rt < \theta lt$	$\theta lt < T_{thresh}$	$\theta lk < K_{thresh}$	$\theta rt > \theta lt$
0	1	0	0	0	0	0
1	1	2	1	1	1	1
2	2	2	3	2	2	2
3	3	3	3	4	3	3
4	4	4	4	4	5	4
5	5	5	5	5	5	0

In order to build a FSM, key events must be chosen to allow transition between states. These events must be reliable and detectable in real time. In the case of the gait cycle, reliability on the occurrence of an event is related to the probability of it occurring in one cycle. Real time detection, in other hand, requires the event to be detectable with little or no delay, not allowing the use of averages due low sampling rate available. As explained above, transitions will be triggered by orientation thresholds individually calibrated from the four IMU placed on each legs thigh and shank. They are set in a sequence that allows knee angle to match movements described in Table 3.2. Interest angles are defined as:

- Right Thigh angle (θrt);
- Left Thigh angle (θlt);
- Right Shank angle (θrs);
- Left Shank angle (θls);
- Right Knee angle (θrk), given by $\theta rk = \theta rt - \theta rs$;
- Left Knee angle (θlk, given by $\theta lk = \theta lt - \theta ls$;

Table 3.4 describes the FSM as a transition matrix. This notation will facilitate the proposition of other transitions in the future. Additionally, figure 3.9 presents a graphical representation. The states are then linked using interest angles and calibrated thresholds. Threshold values must be calibrated according to the patients range of motion and gait speed, and will be defined as:

- T_{thresh}: Thighs threshold angle;
- K_{thresh}: Knees threshold angle;

Figure 3.10 shows fluxogram of the supervisory control routine. It is an implementation of the abstract FSM, therefore, presents some differences when regarding synchronicity. Also, note that although the FSM processing is synchronous, data acquisition and type conversion takes place asynchronously and independently, saving data in variables that can be read by the supervisory code.

Calibration of thresholds was performed manually and individually for each test subject before a data acquisition session. It consisted in visually analyzing interest angles over time with the *rqt_plot* ROS tool and graphically defining the movement ranges. Although it is a time consuming and not so accurate process, it can be later automated in future development.

For validating phase detection, an offline simulation test was conducted. The ROS platform allows saving messages from topics with time stamps with *$ rosbag record -a* command. Once saved, it can be played back in

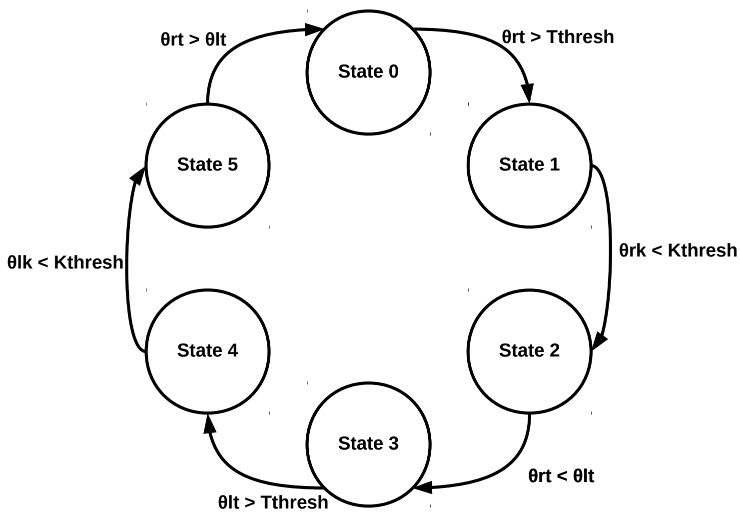

Figure 3.9: State machine of the supervisory control node.

the environment and all messages are published at the same rate, while other nodes listen and run as if data was real time. Angular thresholds were then tuned according to subjects range of motion and gait speed. Accuracy was defined as the quotient of the number of cycles detected by the number of strides (two steps).

3.5 FES ACTIVATION

The system aims to achieve knees extension, flexion and rigidity (for support) by activating FES channels attached to both quadriceps and hamstrings in each leg using superficial FES. As previously explained, superficial FES is a non-invasive method that makes the system not only safer, but more accessible in terms of setup, preparation and financially.

Table 3.5 proposes an on-off muscle group stimulation by state. Each muscle group is activated by an independent electrical stimulation channel. Channels stimulation parameters are: pulse width, amplitude, waveform and frequency. They remain constant, except for pulse length, which is used to control channel activation. When it equals zero, channel is off, and other parameters become irrelevant. Stimulation amplitude must be calibrated previously for each individual in order to achieve satisfactory contraction, and within safe current limits. Parameters can be found in Table 3.6.

The binary activation is a simplified and functional actuation that allows evaluating the FSM in the first place. For future development, states may contain individual control strategies.

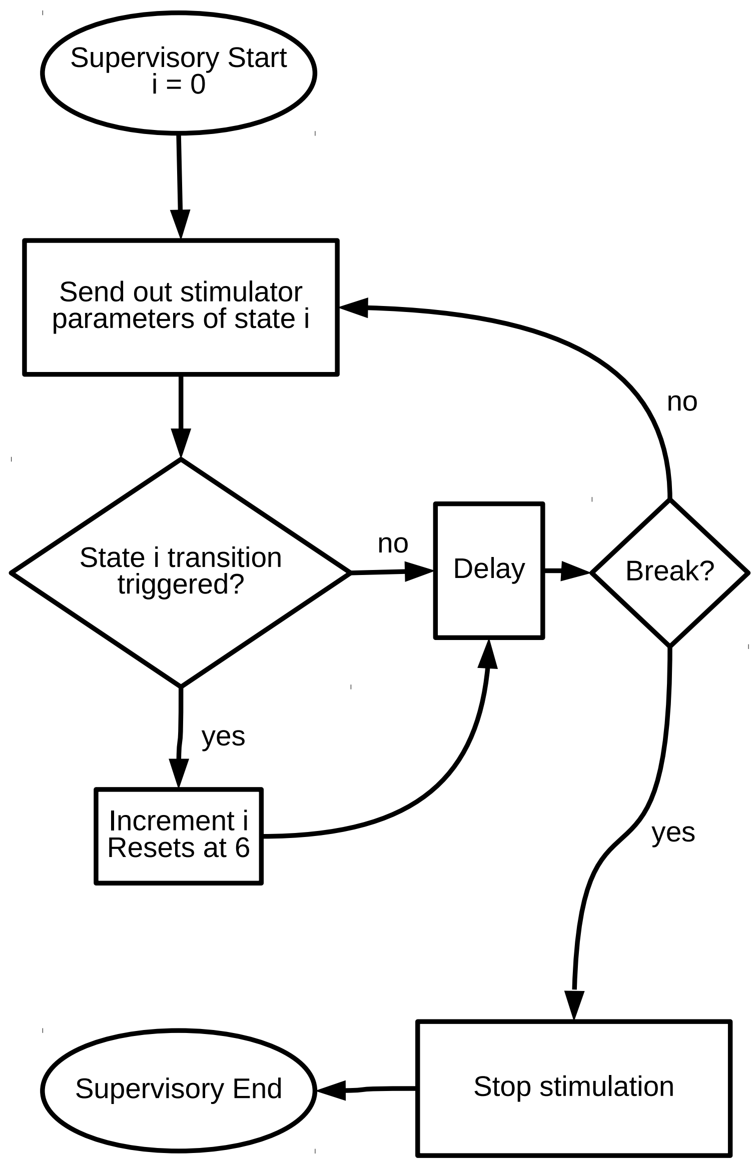

Figure 3.10: State machine of the supervisory control node.

Table 3.5: Correlation between any given state and each channel activation by controlling pulse length.

State	Right Leg		Left Leg	
	Quadriceps	Hamstrings	Quadriceps	Hamstrings
0	OFF	ON	ON	OFF
1	ON	OFF	ON	OFF
2	ON	ON	ON	OFF
3	ON	OFF	OFF	ON
4	ON	OFF	ON	OFF
5	ON	OFF	ON	ON

Table 3.6: Electrical stimulation parameters per activation state. Note that if pulse width equals zero, the other parameters are irrelevant.

Activation	Pulse Width	Pulse Amplitude	Frequency	Wave Form
ON	$500\mu s$	Individually Calibrated	$50Hz$	Rectangular
OFF	$0\mu s$	Individually Calibrated	$50Hz$	Rectangular

4 RESULTS

This chapter aims to present the results obtained during phase detection simulation performed offline and qualitative tests. Also, here is a brief quantitative analysis of the detection system performance.

4.1 GAIT DETECTION EVALUATION

The data collection routine was performed in three healthy adults (HB, 24 years old, 1.83m; RL, 25 years old, 1.70m; MM, 26 years old, 1.59m). It consisted in strapping the four IMU to both legs thighs and shanks, as shown in Figure 3.3 and running the detection system. Except the stimulation node, all the system was executed via SSH using another computer connected to the same WI-FI network. Additionally, the command $\$rosbagrecord - a$ was used to record every message in each running topic and save it with a time-stamp in a $.bag$ file. The file can be executed either in the ROS environment or processed in MATLAB for post processing and generating plots. A MATLAB script allowed a visualization of the interest angles, states and stimulation parameters as shown in Figures 4.1, 4.2 and 4.3.

The three data sets, HB ,RL and MM were processed offline in MATLAB. The total number of strides was counted during data collection and visually confirmed in generated graphs. The accuracy of the gait detection system for each data set is then defined as the quotient of detected cycles and counted strides:

$$Accuracy = \frac{Detected\ Cycles}{Counted\ Strides}$$

Accuracy results, total number of strides and counted FSM cycles obtained for each data set are presented in Table 4.1.

4.2 QUALITATIVE EXPERIMENTATION

Additionally, the full protocol, including electrical stimulation, was tested in three members of the research team. For that purpose, the system was executed using the notebook along with the wireless hub for receiving IMU data. A treadmill allowed the subjects to walk without pulling stimulation channels cables and perform a regular gait with complete range of motion. It was set to minimum speed, at $2km/h$.

Before each trial, electrodes were carefully placed in the upper and lower portions of both quadriceps and

Table 4.1: Electrical stimulation parameters per activation state. Note that if pulse width equals zero, the other parameters are irrelevant.

Data Set	$T_{thresh}(^o)$	$K_{thresh}(^o)$	Total Strides	Counted Cycles	Accuracy (%)
HB	10	12	12	7	58.3%
RL	10	10	11	10	90.9%
MM	8	10	15	13	86.6%

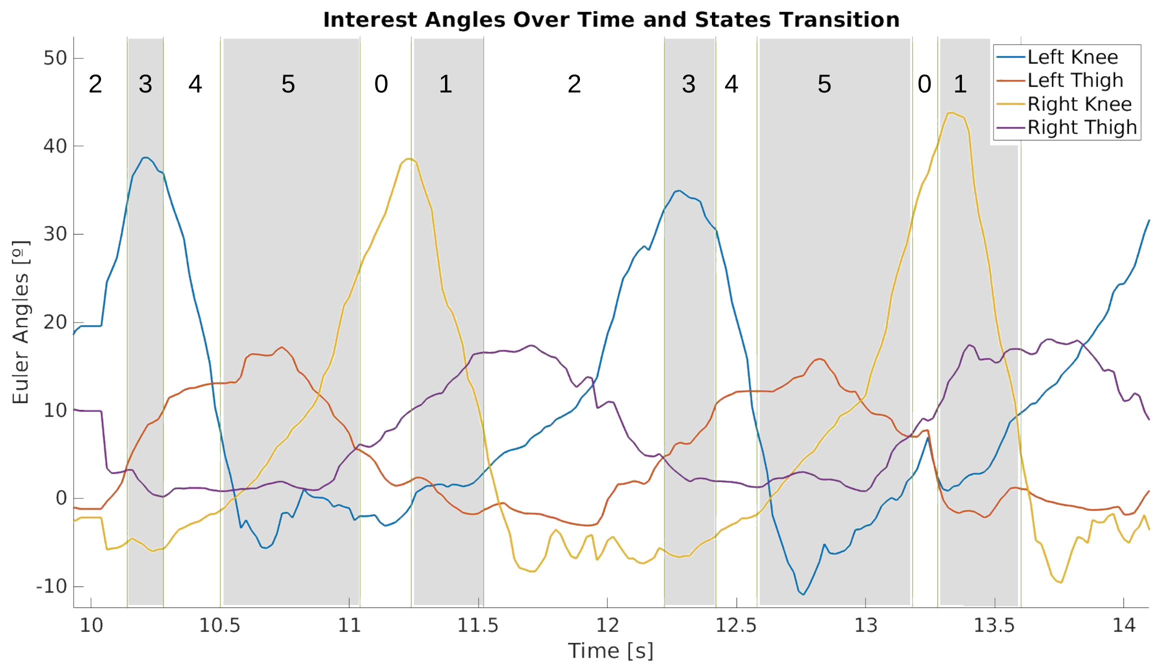

Figure 4.1: The figure shows a time window of the offline processed RL dataset. Interest angles of both knees and thighs that are used to trigger events in the FSM. States are shown at the top of the curves and in gray stripes.

hamstrings, as shown in Figure 3.5. Using the therapeutic mode of the stimulator, parameters were set as in Table 3.6 with increasing current amplitude. In case of discomfort or ineffectiveness, electrodes were slightly moved around and current amplitude values reset. The process was repeated until muscle contraction was perceptible for every channel.

Because there is no body weight support, full muscle contraction was avoided by limiting the current to perceptible levels. This decision was taken in order to avoid that involuntary muscle contraction would compromise subjects balance and safety while walking on the treadmill.

Subjects reported the electrical stimulation channels to activated at the right moments for most times, especially when performing a more exaggerated knee movement range. As observed in previous simulation, they also reported that eventual stagnation of the stimulation pattern.

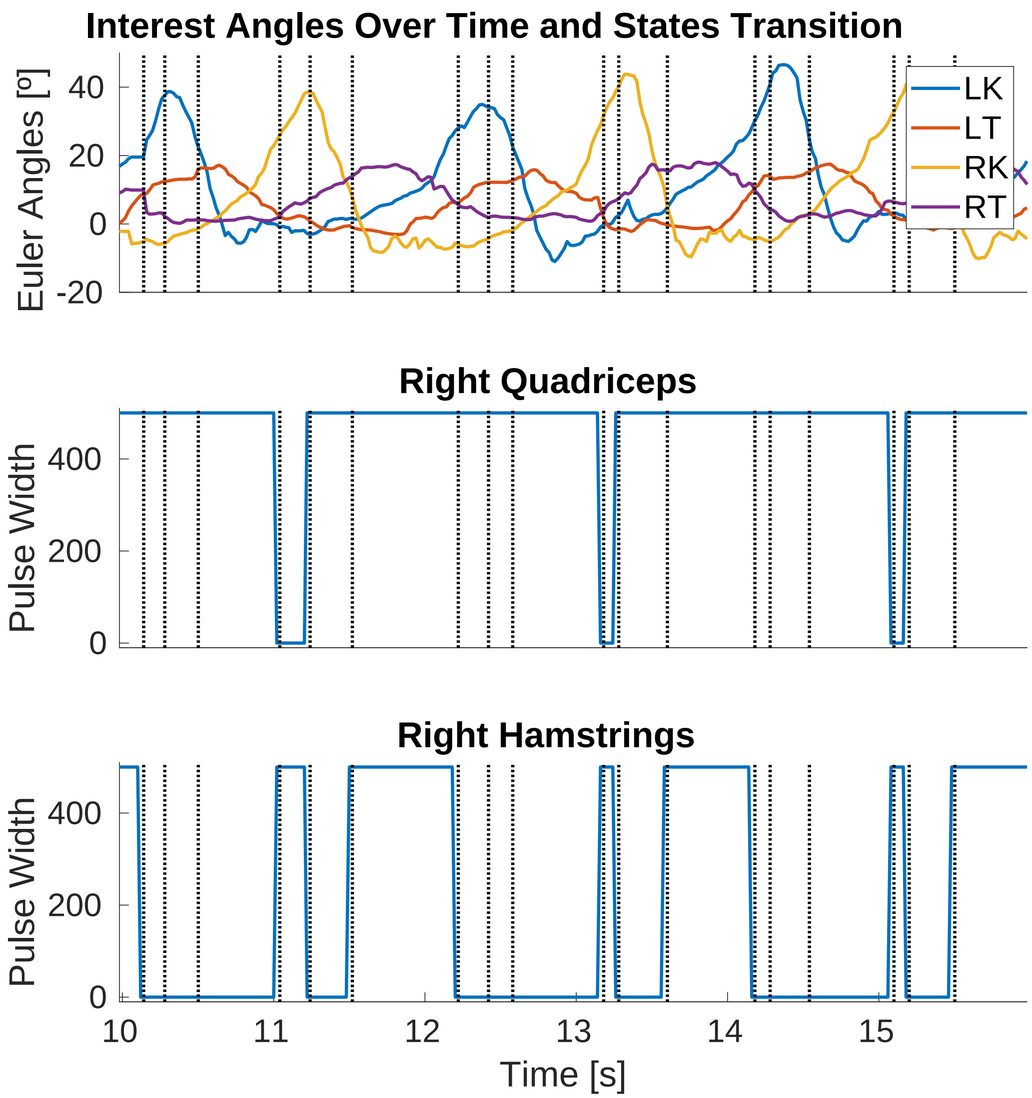

Figure 4.2: The figure shows three graphs lined up vertically sharing the same time axis. Interest angles and states transitions are shown at the top graph. The two following graphs show FES pulse width levels for the right leg that are sent out from the supervisory controller to the stimulator. Interest angles are represented as acronyms: LK: left knee, LT: left thigh, RK: right knee and RT: right thigh.

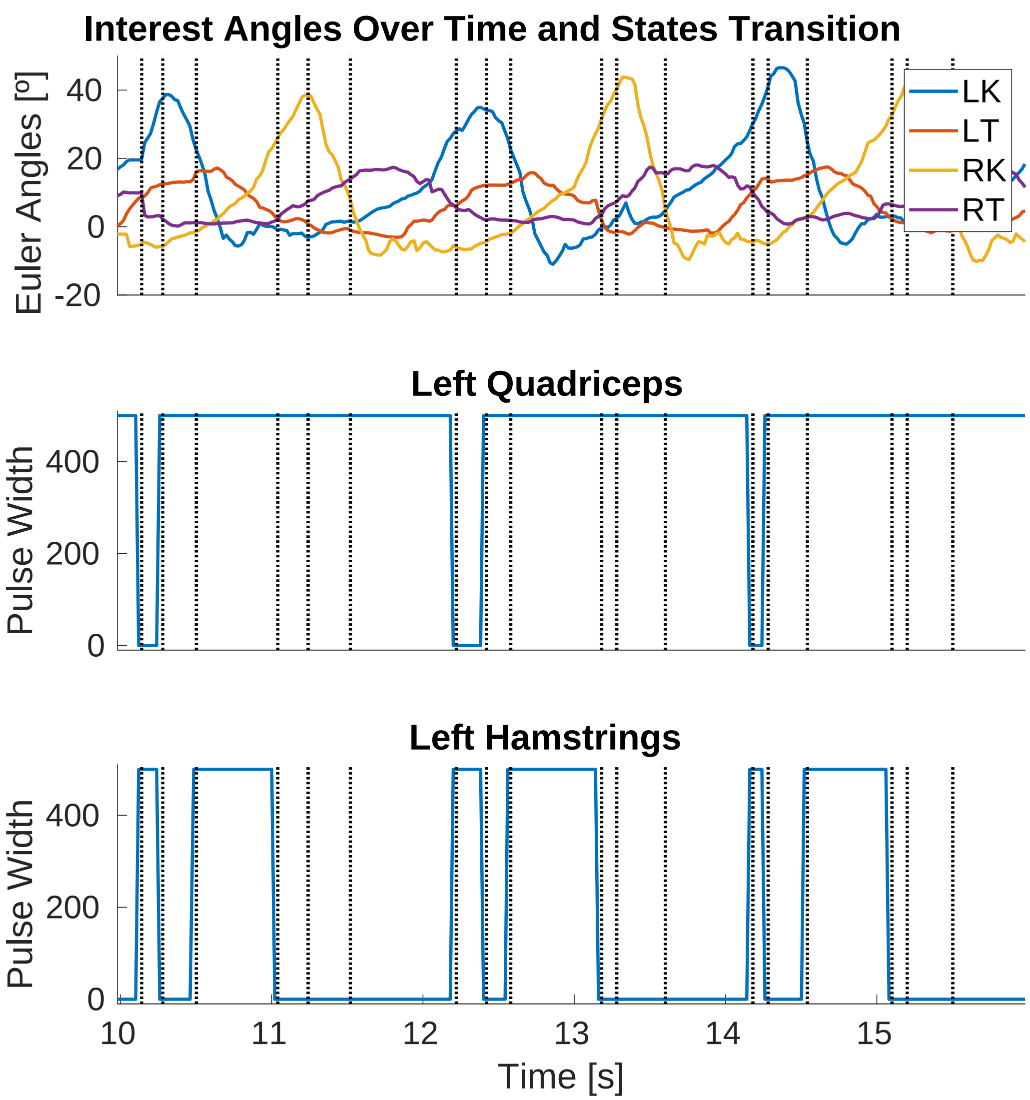

Figure 4.3: The figure shows three graphs lined up vertically sharing the same time axis. Interest angles and states transitions are shown at the top graph. The two following graphs show FES pulse width levels for the left leg that are sent out from the supervisory controller to the stimulator. Interest angles are represented as acronyms: LK: left knee, LT: left thigh, RK: right knee and RT: right thigh.

5 DISCUSSION

This section is dedicated to discuss results obtained in the previous chapter. Improvements and suggestions will be presented as to give directions for future developments of the system in question.

5.1 ACCURACY

The values of accuracy showed in table 4.1 are far from optimal. In order to allow and aid a therapy session, detection rates should, ideally, be above 90% [40][18]. Above is explained how a misdetected event propagates possibly increasing the impact on the accuracy and some improvements that could be applied to get better detection rates.

5.2 MISDETECTION

From simulation, it can be observed in Figure 3.9 that a missed event will cause the FSM to stagnate for at least one full cycle. A misdetection can be caused by a faulty sensor, uncalibrated thresholds or incomplete step, also causing the electrical stimulation patterns to stagnate and possibly difficulting movement until the next transition.

From qualitative experimentation, subjects reported that the above problems indeed occurred. As electrical stimulation was being performed at lower amplitude levels, it would not compromise the gait, but it was noticeable. Note that, while performing tests including electrical stimulation, the IMU was limited to a $15Hz$ sampling rate, what may have compromised, in part, the event detection.

5.3 OTHER CONSIDERATIONS

As the system aims for a rehabilitation environment, some safety measures must be taken. Regarding the software error handling, safety checks could be performed within the supervisory controller. If needed, it could then suspend the electrical stimulation and signalize to the therapist. That could be applied, for instance, if odd orientation data was being generated, or electrodes were loose. So far, the supervisory controller did not include any safety checks within its software. As shown in Figures 5.1 and 5.2, IMU are succeptible to misplacement and may cause the state machine to go to any state when getting looser.

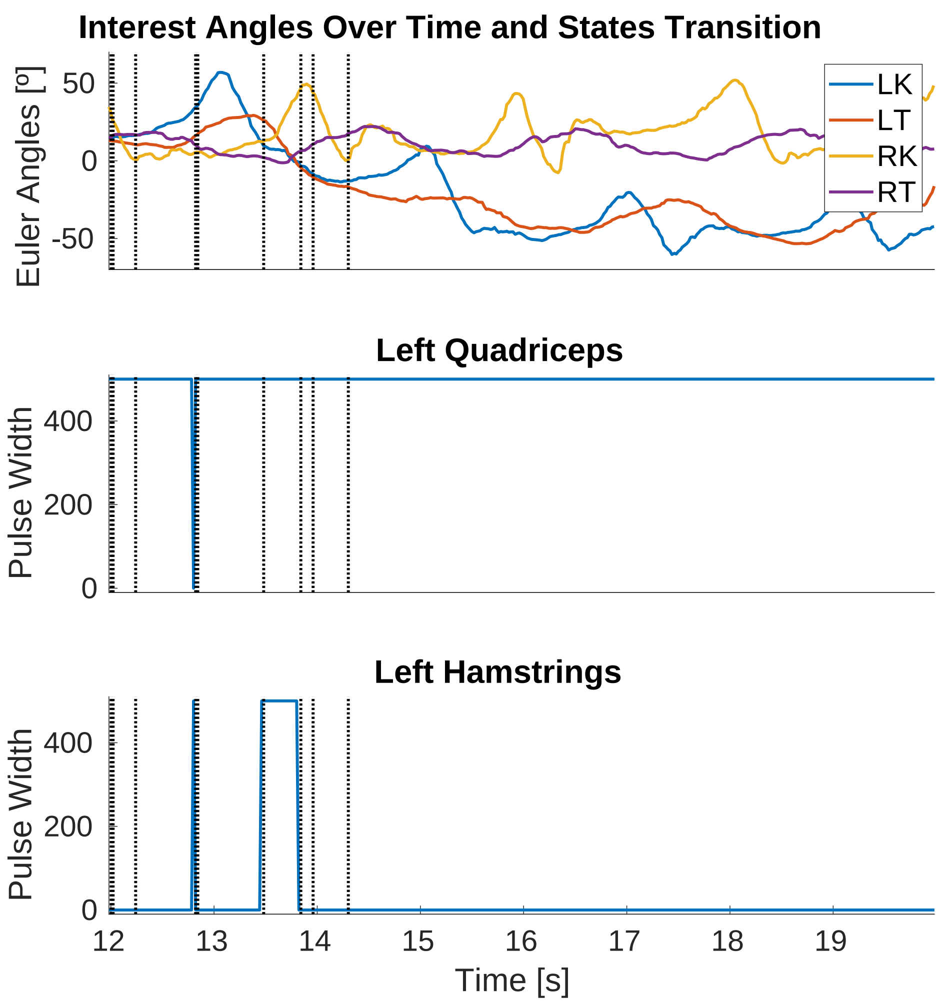

Figure 5.1: Orientation data drifting caused by sensor misplacement and fall - left leg.

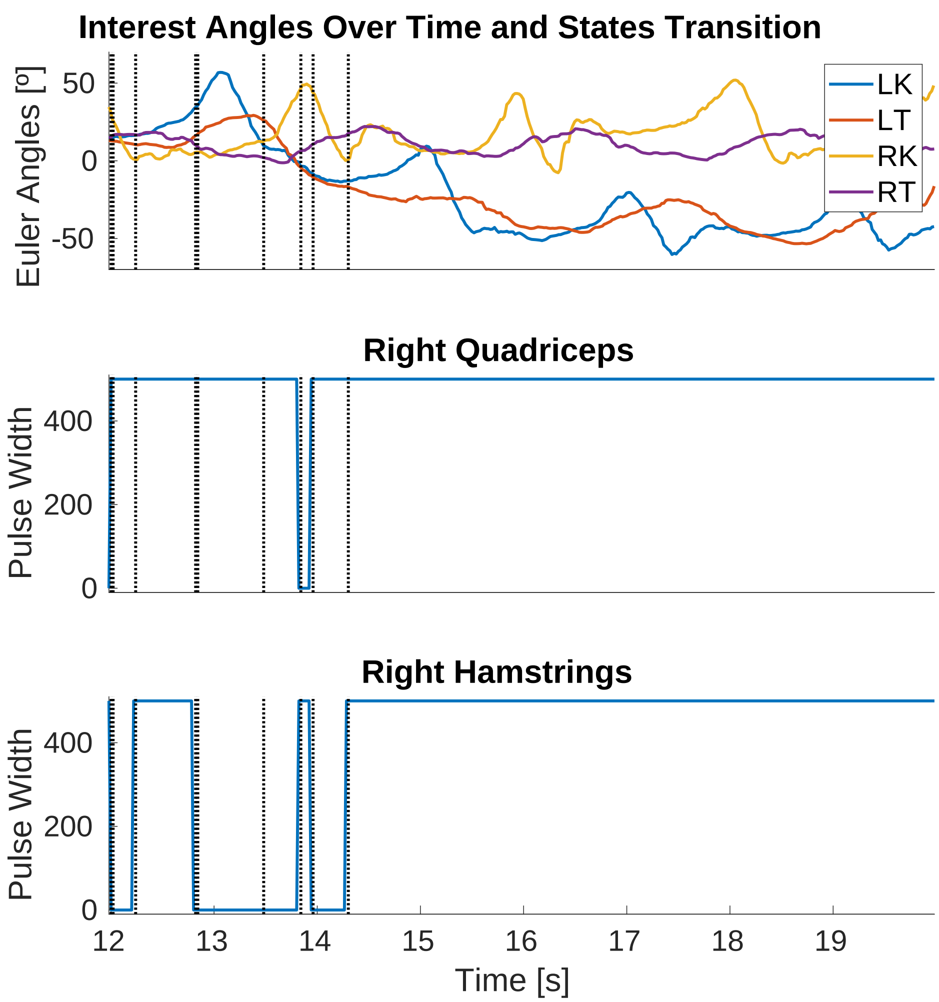

Figure 5.2: Orientation data drifting caused by sensor misplacement and fall - right leg.

6 PROPOSED IMPROVEMENTS FOR FUTURE WORK

Here are presented a series of possible improvements to be implemented. They aim to preserve the basic structure with the same premises of robustness and fast system response.

6.1 STATE MACHINE

6.1.1 Adding Transitions

Small but significant changes could be applied to the state machine and possibly improve the accuracy results. In order to minimize the cost of one event non-detection, it would be possible to associate more transitions between states. It would allow the system to skip states instead of stagnating in a given state until the next same transition occurred again, one cycle ahead. As observed by test subjects during qualitative experimentation, the FSM stagnation also difficults the movement. Additionally, accuracy would then need to be computed considering the number of detected and total events, not only strides. A simple illustration of additional transitions between states can be seen in and Figure 6.1.

6.1.2 Parallel State Machines

Although the FSM was designed to operate and actuate both legs symmetrically, another approach could be explored, making gait monitoring independent for each leg. It could consist in the use of two FSM. It could be achieved by programming the two FSM to execute in simultaneously, or by making a parallel composition of them. It could allow each leg to be monitored and stimulated more independently, which could show itself to be an advantage when concerning irregular asymmetrical gaits. Additionally, other events and transitions may have to be defined, as there is, in fact, dependency between phases of both legs.

6.2 DATA ACQUISITION

6.2.1 Sensors

Some changes could be worked regarding the sensors. As previously described, sampling rates showed as a problem that was partially resolved. Still, a better data acquisition rate could benefit the system presented, as allow further data processing and utilization of other inertial features. It could possibly be achieved by either a software review or sensors hardware update. For that purpose the ROS architecture is very adequate and would greatly facilitate changing or adding modules of sensors and stimulation.

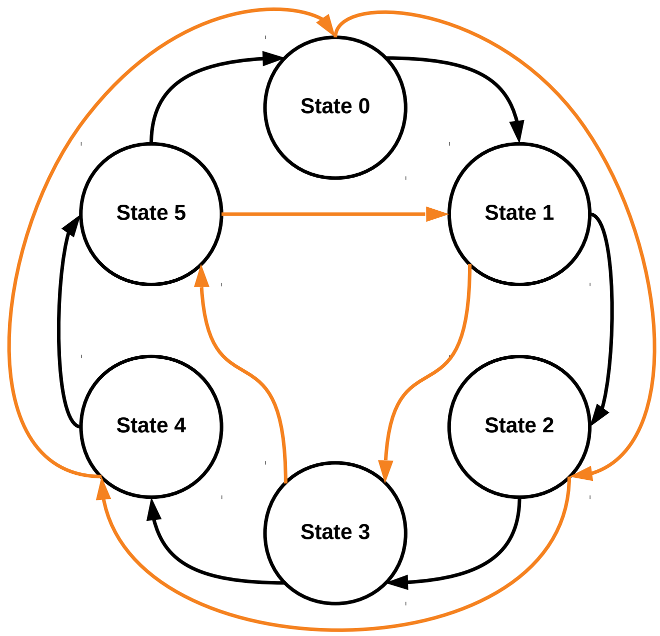

Figure 6.1: Improved state machine with more transitions that allow system to correct the state before a full cycle.

6.2.2 Data Processing

Also, additional data processing could help avoiding some of the problems encountered during data analysis. Specifically, regarding the angle drift that was observed in some cases, that is represented in Figures 5.1 and 5.2. Misplacements and accommodation of sensors is common. It is safe to assume that, in a controlled environment, patients will find themselves mostly in the upright position. Therefore, angles should be always oscillating around a fixed value. In order to correct that and make the system more robust, a solution would regard removing some of the low frequency components that cause the signal to drift and cause the signal not to reach the pre-determined event thresholds.

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