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Kinematic and Electromyographic Analysis of Free Kicks in Football

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Abstract

Football as the most played sport in the world, should be the greatest force in the development of sport and the science involved in it. However, football has always possessed an "aura" of simplicity. In spite of that, the clubs that have focused on this, have seen their efforts rewarded, both in trophies and in monetary terms.

In this study, with the help of two clubs from the Portuguese Football League, a biomechanical analysis of the performance of direct Free Kicks by players of different ages and in different zones of the field was performed.

The kinematic and electromyographic parameters of Free Kicks performed by eight players from the under 23 and B teams of one of the most well regarded Portuguese football team, were evaluated. These kinematic parameters consisted of the angle of the supporting leg, the last stride length and the distances covered, the maximum velocity and the average speed of the movement of these joints. In the electromyography we analyzed three leg muscles.

Our results revealed that the angle of the supporting leg seems linked to impact absorption of the movement performed. We also concluded that the greater the distance traveled by the foot, and of the last stride, the greater the ball speed. These parameters also seem to be linked with the body rotation. It was also observed that the medial gastrocnemius is activated earlier and longer than the quadriceps muscles, in all pitch zones. Free Kicks from greater distances show greater muscle activation than Free Kicks from nearest zones, while in laterality, no major changes were observed.

These findings reinforce that the study of this field can still evolve a lot, and that a greater investment by sports teams and researchers in the development and expansion of knowledge in sports performance analysis can offer advantages that, in these competitions, are often invaluable.

Keywords: Performance Analysis, Biomechanics, Electromyography, Sports Science, Football

Resumo

A análise de performance e a ciência desportiva, tal como o avanço da tecnologia no desporto, tem permitido, em vários desportos, o desenvolvimento das equipas e dos jogadores. Quando um clube decide investir na área de análise de performance rapidamente consegue adquirir as ferramentas que lhe permitem ultrapassar os seus rivais em nível competitivo, de desenvolvimento e até financeiro. O futebol como desporto-rei e como o desporto mais jogado em todo o mundo deveria ser a maior força no que toca ao desenvolvimento do desporto e da ciência envolvida neste. No entanto, o futebol sempre possuiu uma certa "aura" de naturalidade, não se focando em melhorar através da ciência e da tecnologia. Contudo, os clubes que se focaram nesta vertente viram os seus esforços recompensados, tanto em troféus como em termos monetários. O Liverpool F.C. após começar a apostar nestas tecnologias tornou-se campeão inglês após 30 anos e venceu a Liga do Campeões, enquanto que em termos monetários o valor dos seus jogadores aumentou em 236 milhões de euros. Ao nível português o S.L. Benfica destaca-se nesta área, arrecadando seis ligas portuguesas e grandes percursos na Liga dos campeões desde o ano 2010, tal como um total de mil milhões de euros arrecadados por venda de jogadores do seu plantel desde o ano 2000.

Os estudos mais comuns na área de análise de performance em termos biomecânicos focam-se em parâmetros cinemáticos e eletromiográficos, especialmente estudos focados em Livres Diretos e bolas paradas (Livres Diretos, cantos, penáltis) no geral. No entanto, poucos são aprofundados ao ponto de apresentarem informação pertinente não apenas para a literatura, mas para as equipas em si e poucos apresentam informação eletromiográfica e cinemática em conjunto. Neste estudo, com a ajuda de dois clubes da Liga Portuguesa de Futebol, foi realizada uma análise biomecânica da execução de Livres Diretos por jogadores de diferentes idades e em diferentes zonas do campo, tanto em distância como em lateralidade, com o objetivo de obter informação dos fatores envolvidos na execução destes remates e ganhar um entendimento das divergências biomecânicas entre estes diferentes parâmetros. Antes de realizar esta análise, foi executada uma análise geral de 3000 Livres Diretos realizados na Segunda Divisão Portuguesa ao longo das temporadas 18/19, 19/20 e 20/21, para se retirar informação acerca da eficácia dos Livres Diretos e entender qual a melhorar maneira de realizar a nossa análise biomecânica.

Nesta análise, foram avaliados os parâmetros cinemáticos de um total de 123 Livres Diretos (72 da equipa de sub-23 e 51 da equipa B) e os parâmetros eletromiográficos de 37 livres Diretos (16 da equipa de sub-23 e 21 da equipa B), de um total de oito jogadores da equipa sub-23 e equipa B de uma das melhores equipas da Liga Portuguesa. Estes Livres Diretos foram executados de quatro zonas do campo: duas zonas dianteiras à entrada da área, uma mais para a esquerda e outra para a direita, e duas zonas mais afastadas com a mesma lateralidade. Estes parâmetros cinemáticos, analisados no software Kinovea, consistiram no ângulo da perna de suporte aquando do impacto do pé dominante com a bola, na distância da última passada, nas distâncias percorridas pelas articulações da perna (i.e., anca, joelho e tornozelo), na rapidez do movimento destas articulações e na velocidade máxima analisada destas articulações durante o movimento. Na eletromiografia analisou-se, através do software OpenSignals e com o uso de um BITalino para captar o sinal eletromiográfico, o papel de três músculos: o gastrocnémio medial, o vasto lateral e o vasto medial, em termos da raiz quadrada média do sinal e da sua duração. Adicionalmente, o momento de ativação muscular no movimento também foi investigado.

Realizaram-se, através de testes não paramétricos de hipótese nula de Mann-Whitney, comparações dos dados cinemáticos e eletromiográficos entre a equipa sub-23 e a equipa B, entre as zonas mais dianteiras e as zonas mais afastadas da baliza, entre as zonas mais à esquerda e mais à direita. Também foi analisada a existência de relações entre os parâmetros: ângulo da perna de suporte durante o impacto do pé dominante com a bola, distância da última passada e distância percorrida pelo pé durante o movimento, com a velocidade do pé e por consequência com a velocidade da bola.

Os resultados da análise geral de 3000 Livres Diretos revelaram que cerca de 73% destes são executados como cruzamentos, sendo que remates equivalem apenas a 21% de todos os Livres Diretos. Estes resultados estão intrinsecamente ligados à localização dos livres observados onde cerca de 54% são executados das zonas laterais do campo e 17 % das zonas mais centrais mas afastadas da baliza. A maior probabilidade de golo por zona observada ocorreu nas zonas mais dianteiras do campo, em especial na zona mais central e mais dianteira com 4,5% de chance de golo por Livre Direto. Observamos que ao considerar apenas os Livres Diretos executados como remates a probabilidade de exisitr golo aumentou na maioria das zonas dianteiras, com resultados surprendentes em que as zonas laterais demonstraram maior probabilidade de golo do que as zonas interiores do campo. Finalmente também observamos que a maioria dos Livres Diretos são direcionados aos ângulos superiores da baliza, com uma menor quantidade a serem batidos aos cantos inferiores e ao centro da baliza.

Os resultados biomecânicos desta dissertação mostraram que existem fatores cinemáticos e eletromiográficos envolvidos na marcação de Livres Diretos significativamente diferentes entre idades e zonas do campo, tanto em distância como em lateralidade. Observou-se que o ângulo da perna de suporte parece estar intrinsecamente ligado à quantidade de absorção do impacto do movimento que é necessário realizar, observando-se um ângulo mais elevado quando se aplica maior força, ou seja uma ângulo maior foi observado nas zonas mais afastadas da baliza onde mais força é necessária e em zonas onde maior rotação do corpo é necessário. Também se concluiu que quanto maior a distância percorrida pelo pé ao longo do movimento, e quanto maior a distância da última passada, maior é a velocidade do pé e por consequência a velocidade da bola. Estas maiores distâncias percorridas também parecem estar ligadas à rotação do corpo, sendo que quando apresentam maior valor a rotação esperada será maior. Observou-se também que o gastrocnémio medial é ativado mais precocemente que os músculos do quadríceps (vasto medial e vasto lateral), e que a sua ativação é mais longa, independentemente da zona do campo. Livres batidos de maiores distâncias mostram uma maior ativação muscular que os Livres Diretos batidos de zonas mais dianteiras, enquanto que, em termos de lateralidade, não se observaram grandes alterações em termos de ativação muscular.

Concluiu-se que vários fatores técnicos e biomecânicos na performance de Livres Diretos diferem quando se comparam jogadores de diferentes idades e equipas, tal como entre diferentes distâncias à baliza ou em termos de lateralidade, tanto numa visão cinemática como numa visão eletromiográfica. Informação pertinente não previamente investigada nesta área foi observada e aparenta ser de grande interesse para adicionar à literatura existente.

Estas conclusões reforçam que o estudo desta área ainda pode evoluir bastante, sendo que um investimento maior por parte das equipas desportivas e de investigadores no desenvolvimento e expansão do conhecimento na análise de performance desportiva pode oferecer vantagens que, nestas competições, são muitas vezes inestimáveis.

Palavras-chave: Análise de Performance, Biomecânica, Eletromiografia, Ciência do Desporto, Futebol

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Acronyms

EMG – Electromyography. 2, 14, 15, 16, 17, 24, 25, 26, 29, 30, 33, 34, 35, 39, 45, 46, 47, 48, 51, 52

ACh – Acetylcholine. 11

MUAP – Motor Unit Action Potential. 14, 15, 16

MUAPT - Motor Unit Action Potential Train. 15, 16

LF – Left Far. 27, 28

LN – Left Near. 27, 28, 36

RF – Right Far. 27, 28

RN – Right Near. 27, 28, 36

CLF – Center Left Far. 27, 28, 29, 39, 41, 42, 46, 47, 50

CLN – Center Left Near. 27, 28, 29, 36, 38, 39, 41, 42, 46, 47, 50

CMF – Center Middle Far. 27, 28

CMN – Center Middle Near. 27, 28, 36, 37, 38

CRF – Center Right Far. 27, 28, 29, 39, 41, 42, 46, 47, 50

CRN – Center Right Near. 27, 28, 29, 36, 38, 39, 41, 42, 46, 47, 50

RMS – Root Mean Squared. 33, 34, 46, 47, 48

1. Introduction

1.1. Context and Motivation

There has always been a contrast between football and other popular sports. Some sports that are comparatively less popular have focused in bettering themselves with the use of data analytics, performance analysis, and biomechanical analysis. Football has not been able to fully take that step. On the other hand, football is the crown jewel of sports, it is the sport of the "people", the "Beautiful Game", because of its unpredictability and ability to bring communities together. Because of this, football has possessed an aura of simplicity and naturality that became hard to surpass.

Presently, this problem seems to be dissipating. Over the last two decades, football seems to be starting to take the steps to take its place on the top of sports and biomechanical research, as it should be, as the most played sport in the world. This advancement comes as a result of the success that teams that have embraced data analytics and technology's help have had. One of the biggest examples being Liverpool FC, which in 2010 was acquired by the owners of the Boston Red Sox baseball team, that already used data analytics for their advantage, deciding to replicate the process at Liverpool. With an investment in data analytics and other areas, the team became the domestic league champion in the most competitive league in the world after a 30 year drought, also winning the biggest European team trophy in the Champions League, whilst simultaneously increasing their players' monetary value by over 236 million euros (pre-COVID-19) [1]. In Portugal, this field has not been a priority. However, clubs like Benfica must be considered experts domestically in the used of data analytics and biomechanical data, helping them to six League trophies since 2010 and very good Champions League runs, and perhaps the main result of a whopping 1 billion euros in sold players since the year 2000. It becomes apparent that to compete at the highest level, both in the league competition and in the transfer market, teams are going to start to embrace technology and research, as it reaps mainly advantages. In the next few years, we expect to see a boom in the use of these technologies, while clubs that already have done so will keep searching for improvements to existing methods, and as new research and information comes to light there will always be coaches and clubs that implement them to inch past their competition [2].

Football is extremely complex, because it has 22 players in the pitch at the same time and because it is a sport where the ball is mainly always flowing. That is the reason why improvement with use of data analytics and performance data is much easier to implement in set pieces, such as corners, penalty kicks, and Free Kicks. Set pieces correspond to around 33% of all goal contributions. Out of those 33%, around a third corresponds to Free Kicks, resulting on a value of around one in 10 goals scored, with most being performed as crosses and not shots on goal [3]. Free Kicks are, therefore, a very interesting aspect of football. Coaches can study and implement several different tactics just regarding Free Kicks. However, this focuses mainly on the crossing aspect of a Free Kick. What can be done to understand Free Kick shooting in a better way? Unlike most other aspects of the game, coaches have less influence in the performance of a Free Kick shot, depending more on the talent and practice of the player. But what if we could determine underlying biomechanical factors in the players that lead to a better performance? When it comes to this biomechanical assessment, it is to be noted that some studies have been published, although very few. The assessment of kinematic parameters, such as joint velocities and muscle activation, has mainly been investigated separately, and in a laboratory setting. To provide this field the information it

lacks, research on technical and biomechanical parameters of Free kick performance by players in a football pitch (creating a natural setting for players) must be applied.

1.2. Objectives

The main goal of this master's dissertation is to research, identify, and compare the overlying biomechanical factors involved in the performance of football Free Kicks by different aged players, players from different football competitive divisions, and from different pitch locations, either in distance or laterality, based on a biomechanical analysis of video and electromyographic (EMG) data from professional young football players. However, with this dissertation, other secondary goals are also expected to be achieved:

- Contributing to current research in the field of sports performance and football biomechanics, regarding biomechanical parameters, including EMG data.
- Collecting Free Kick data from previous seasons in the football division we are studying in order to gain a better understanding of the importance and efficiency of the Free Kick in the game.

1.3. Structure

There are five chapters in this dissertation. Chapter 1 introduces the dissertation theme, by describing the context and motivation, as well as the dissertation's objectives and structure. The background theory, which is required to support the study, is presented in Chapter 2. Chapter 3 discusses the materials and methods used in this project, including Free Kick data collection, biomechanical data collection and analysis, and EMG data collection and analysis. In Chapter 4 the findings are presented and discussed. Finally, the dissertation comes to a close in Chapter 5 with a summary of the main findings and conclusions, as well as recommendations for future research.

2. Background Theory

2.1. Musculoskeletal System

Our body consists of a lot of different systems, from the nervous to the digestive, but the musculoskeletal system is the one that defines our shape, how our body looks, from a structural perspective, and how it moves and works. Therefore, it could also be referred to as the Locomotor System, seeing as its main function is to gives mobility. The skeleton works as the supporting framework for the body, formed by bones and cartilage, connected by connective tissue structures. Its parts move or are held in specific positions and postures by the skeletal musculature. The skeleton and joints form the passive musculoskeletal system, while the active system is defined by the striated muscles, the tendons, and the sesamoid bones (i.e., small round bone within a tendon that serves to reinforce and decrease stress). Besides their support function, the skeletal elements and joints work as levers for the muscles during movement and, together, the skeletal musculature also function as protection for important organ systems (skull, vertebrae, chest cage) [4].

2.1.1. Skeletal Joints

The human body can be considered rigid as it can maintain a posture and it can also be considered flexible because it can move and change posture. This flexibility comes mainly from our joints, or articulations, which are responsible for providing the mobility previously stated. However, a joint can not only provide mobility, but it is also of upmost importance to provide a degree of stability and, given that different joints have different functions, joints show different combinations of mobility and stability throughout the body. Some joints, such as the shoulder joint (ball and socket), provide maximum mobility, in this case, enabling three planes of movement to the arm. However, this is only possible at the expense of stability, being more vulnerable to injuries, most common dislocations [5]. Joints that only provide movement in one plane, such as the elbow joint, are less complex in mobility, but offer more stability and safety against injury [6]. Finally, there are the joints that offer no relative motion between bones that form the joint, providing maximum stability. The bones in our skull are the best examples of said joints.

Classification of the human skeletal joints can be based on their structure and function. Synarthrodial joints, such as the skull joints, are formed by two bones joined together so tightly that they do not allow any relative motion [7]. Amphiarthrodial joints, the ones between the vertebrae, allow only slight motion and need an intervening substance (cartilaginous or ligament tissue) whose presence eliminates direct bone-to-bone contact. Diarthrodial joints are the most mechanically significant articulations, allowing for several degrees of motion, composed by articular cavities, ligamentous capsules, synovial membranes, and synovial fluid. The articular cavity is the space between the bones and the ligamentous capsule holding the articulate bones together. The synovial membrane is the internal lining of the ligamentous capsule enclosing the synovial fluid that serves as a natural lubricant for the joint - it is a viscous fluid that reduces friction, wear, and tear of the surfaces by limiting the amount of direct contact between them, while also nourishing the articular cartilage lining the surfaces. Finally, the articular cartilage is a specialized tissue that increases load distribution on the joints and provides a wear-resistant surface that absorbs shock better [7]. By their function joints can be categorized as ball-to-socket (hip), condyloid (wrist), hinge (elbow), pivot (proximal

radioulnar, the joint of the forearm), saddle (thumb), and gliding or plane (vertebrae facets), as seen on figure 2.1.

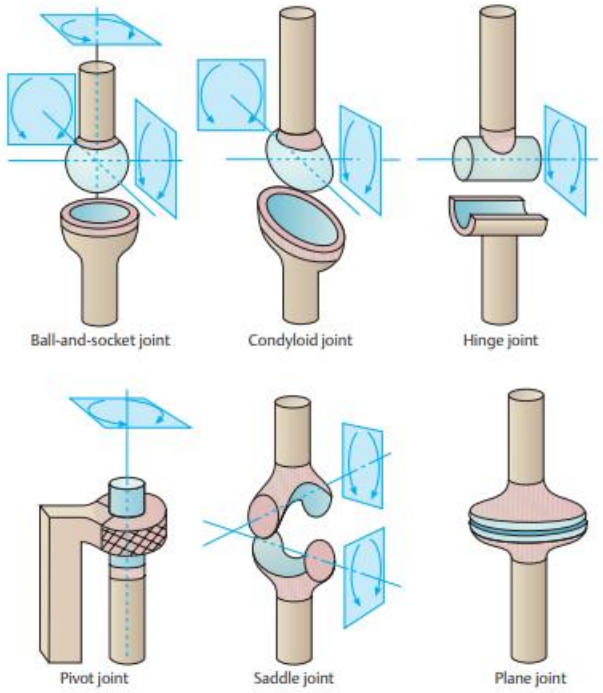

Figure 2.1: Types of joints and their movement directions. (From [3])

2.1.2. Skeletal Muscles

There are over six hundred muscles in the human body, which can be divided into three types: cardiac, smooth, and skeletal. Cardiac muscles are situated around the heart and work by contracting, pumping the blood out of the heart for circulation. Smooth muscles are found throughout the body, such as in the stomach or intestine tracts and do not show any striation. Skeletal muscles are connected to the bones and when contracting allow for movement.

The movement of body segments is a result of forces generated by our skeletal muscles by converting chemical energy in mechanical work. The skeletal muscles are composed by muscle fibers, which consist of myofibrils arranged in parallel. Myofibrils are composed of repeating sections of sarcomeres arranged in series, which are made up of actin and myosin filaments (figure 2.2), resulting in muscles exhibiting a viscoelastic material behavior, showing both solid and fluid-like material properties [8]. They are elastic because when a muscle is stretched and released it will return to its original size and shape, and they are viscous due to their internal resistance to motion [7].

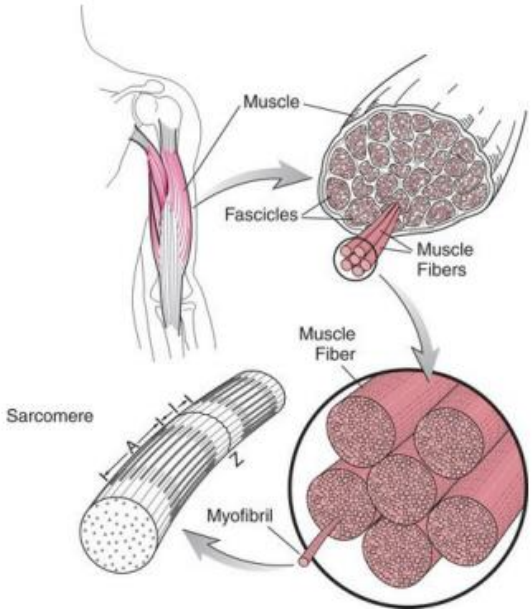

Figure 2.2: Structural Hierarchy of skeletal muscle. Whole skeletal muscles are composed of numerous fascicles of muscle fibers. Muscle fibers are composed of myofibrils arranged in parallel. Myofibrils are composed of sarcomeres arranged in series. Sarcomeres are composed of interdigitating actin and myosin filaments. (From [7])

A skeletal muscle controls relative motion of one segment of the body in relation to another by being attached to, at least, two bones via soft tissues such as tendons or aponeuroses. Under nerve stimulation, its fibers contract and the muscle exerts a pulling effect on the bones to which it is attached. Contraction implies shortening under compressive forces. However, in the muscles, contraction can occur as a result of muscle shortening or muscle lengthening, or with no change in length at all. The result of muscle contraction is always tension, only exerting a pull force and never a push.

Muscle contractions come in several types: concentric contractions occur at the same time as the length of the muscle decreases (biceps during forearm flexion); static contractions occur while muscle length is constant (biceps when the forearm is flexed and held without movement); and eccentric contractions occur as muscle length increases (biceps during arm extension). However, the muscle is only the cause of the movement when it contracts concentrically. The tension generated by a muscle when its length increases is aimed at controlling the movement of the body segments associated with that muscle but is not the cause of said movement. When a muscle contracts but there is no segmental motion, the tension forces balance the effects of applied forces such as gravity (isometric contraction).

The skeletal muscles are also named according to their function during certain activities. If a muscle causes movement through its contraction, it is called an agonist muscle, being the primary muscle responsible for generating the movement itself. On the other hand, antagonist muscles oppose the action of another muscle, while synergic muscles assist the agonist muscle by performing the same joint motion.

2.1.3. Tendons and Ligaments

Tendons and ligaments are fibrous connective tissues that help execute joint motion by transmitting mechanical forces from muscles to bones. Ligaments join bones and provide stability to the joints, as seen on figure 2.3. Unlike the muscles, that can produce mechanical forces, therefore being considered active tissues, tendons and ligaments are passive tissues and cannot actively contract to generate forces [9].

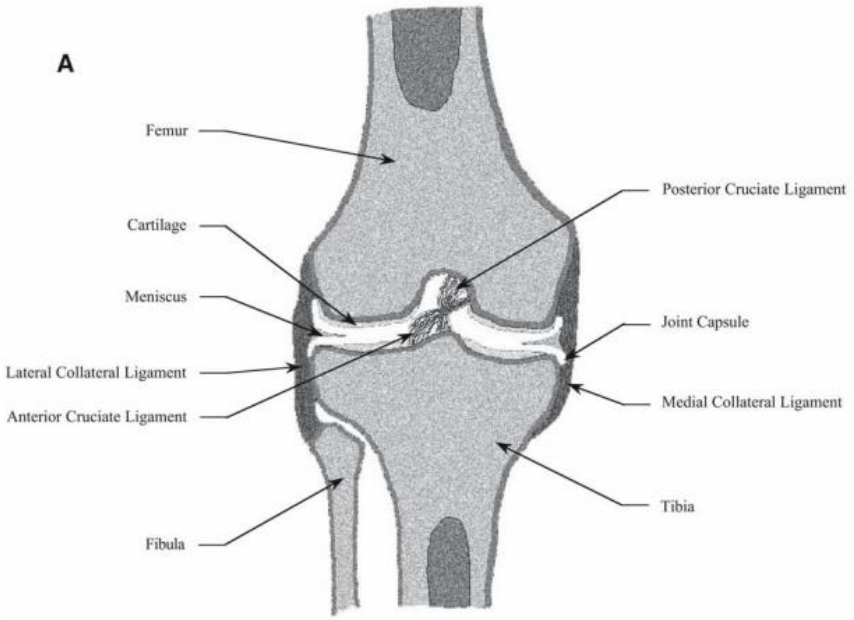

Figure 2.3: Diagram of the knee joint, showing how the knee ligaments connect the bones together. Frontal view of the knee and the location of dense connective tissue, including the anterior and posterior cruciate ligaments, medial and lateral collateral ligaments, and joint capsule in the knee. The patellar tendon (not shown) is found in front of the cruciate ligaments. (From [8])

Around several joints of the human body, there is little space to attach more than one or a few muscles. As such, to accomplish certain tasks, one or a few muscles must, in a joint way, generate and withstand large loads with intensities even larger at regions closer to the bone attachments where the cross-sectional areas of the muscles are small. Compared with muscles, tendons are stiffer, with higher tensile strength, and can endure larger stress. For that reason, around the joints where the space is limited, muscle attachments to the bones are made by tendons, which can support these great loads with little deformations. This property of the tendons allows for transmission of forces to the bones without wasting energy to stretch the tendons.

Ligaments transmit forces from one bone to another, while also providing a stabilizing role for the skeletal joints. Their composition depends on their function and position within the body. Like tendons, they are composite materials containing compressed collagen fibers surrounded by ground substance. Compared to tendons, they often contain a greater proportion of elastic fibers that accounts for their higher extensibility but lower strength and stiffness. Their mechanical properties are quantitively similar to those of tendons.

2.1.4. Hip Mechanics

Given that this dissertation revolves around lower limb biomechanics, a brief introduction to the mechanics of the lower joints is important to have a better understanding of how our body moves when performing the tasks that will be presented later in this work.

Our hip articulation, between the head of the femur and the acetabulum of the pelvis forms a diarthrodial joint. This joint has very high stability due to a relatively rigid ball-and-socket type of configuration, its ligaments, and by the strong muscles that cross it. The femoral head fits perfectly into the deep socket of the acetabulum, with the ligaments of the joint and the labrum (flat rim of fibrocartilage) supporting and holding the femoral head in place as it moves. Although it is characterized by its stability, this joint also allows for great mobility, providing a wide range of motion that is required for tasks such as walking, sitting, squatting, jumping, and kicking. The hip joint allows for flexion and extension, abduction and adduction, and inward and outward rotation movements of the femur. However, some of these movements are constrained by tissue, such as ligaments, muscles, or bone structures of the hip. The articulating surfaces of the head of the femur and the acetabulum are lined with hyaline cartilage that provide some cushioning and minimize friction between them. With age or derangements of the hip, altered force distributions in the joint cartilage can be produced, leading to arthritis [4] [5].

The pelvis is composed by the ilium, ischium, pubis bones, and the sacrum, all of which, at birth, are distinct bones. In adults these bones are fused, forming synarthrodial joints which allow no movement. Movements of the pelvis serve the primary purpose of facilitating the movements of the spine and femurs. There are no muscles in the human body with the purpose of moving the pelvis, while the muscles of the trunk and hip passively move the pelvis.

The muscles of the hip joint (figure 2.4) can be divided into several groups based on their primary functions. The psoas, iliacus, rectus femoris, pectineus, and tensor fascia latae are the primary hip flexors, being responsible for activities such as kicking or running. The gluteus maximus and the hamstring muscles are hip extensors, the hamstrings also work as knee flexors. The gluteus medius and minimus are hip abductors muscles providing the inward rotation movement of the femur, while the adductor longus, adductor brevis, adductor magnus, and gracilis muscles are the hip adductors. Small, deeply placed muscles provide the outward rotation of the femur [7] [10].

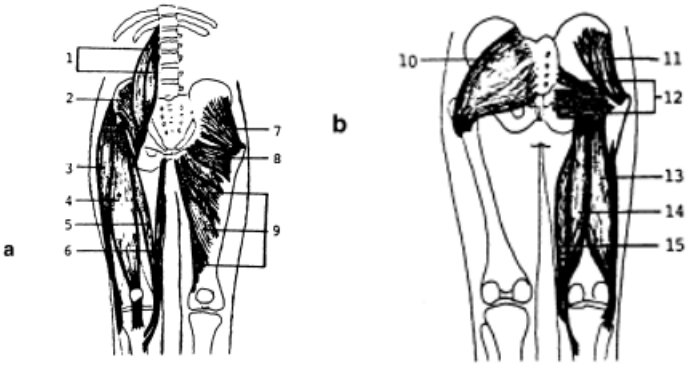

Figure 2.4: Muscles of the hip (a) anterior and (b) posterior views: (1) psoas, (2) iliacus, (3) tensor fascia latae, (4) rectus femoris, (5) sartorius, (6) gracilis, (7) gluteus minimus, (8) pectineus, (9) adductors, (10, 11) gluteus maximus and medius, (12) lateral rotators, (13) biceps femoris, (14) semitendinosus, (15) semimembranosus. (From [6])

2.1.5. Knee Mechanics

The knee joint is the largest in the whole body, being a modified hinge joint. In addition to flexion and extension movements of the leg in the sagittal plane, the knee allows some inward and outward rotation. Located in the middle of the leg, the knee joint is designed for large loads and is an essential component of the human locomotion. It is, however, extremely prone to injuries.

The knee joint is composed of two joints that work together: the tibiofemoral joint and the patellofemoral joint. The tibiofemoral joint has two distinct articulations between the medial and lateral condyles of the femur and the tibia, separated by layers of cartilage, the menisci. The lateral and medial menisci eliminate bone-to-bone contact between the intervening bones, working as shock absorbers. The patellofemoral joint is the articulation between the patella and the anterior end of the femoral condyles. The patella is a bone in the anterior zone of the knee, that is held in position by the quadriceps tendon and the patellar ligament. This gives the quadricep muscle a mechanical advantage, improving its pulling effect on the tibia through the patellar tendon. The stability of the knee is provided by an intricate ligamentous structure, the menisci and the muscles that cross the joint, resulting in a sufficiently stable joint, but that is very prone to injuries from extreme load or overly extended or rotated movements. Therefore, most knee injuries are characterized by ligament and cartilage damage on the medial side.

The muscles that cross the knee, shown in figure 2.5, protect it, but also provide internal forces for movement and control. The muscular control of the knee is produced mainly by the quadriceps muscles and the hamstring muscles. The quadriceps muscle group is composed by the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius muscles. The rectus femoris attaches at the anterior-inferior iliac spine and the patella, and its primary actions are the flexion of the hip and extension of the knee. The vastus lateralis, medialis, and intermedius muscles connect the femur and tibia through the patella and all work as extensors. The bicep femoris, semitendinosus, and semimembranosus muscles form the hamstring muscle group, that helps control the extension of the hip, flexion of the knee, and some inward and outward rotation of the tibia. The semitendinosus and semimembranosus muscles have proximal attachments on the pelvic bone and distal attachments on the tibia, while the bicep femoris has proximal attachments on the pelvic bone and the femur, and distal attachments on the fibula. The other muscles of the knee are the popliteus, the sartorius, the gracilis, the gastrocnemius, and the plantaris [7] [11].

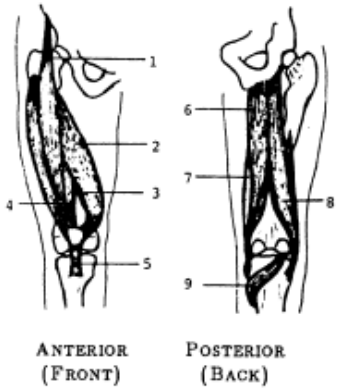

Figure 2.5: Muscles of the knee: (1) rectus femoris, (2) vastus medialis, (3) vastus intermedius, (4) vastus lateralis, (5) patellar ligament, (6) semitendinosus, (7) semimembranosus, (8) biceps femoris, (9) gastrocnemius. (From [6])

2.1.6. Ankle Mechanics

The ankle is the grouping of three bones: the tibia, the fibula, and the talus of the foot. As the knee, the ankle joint is responsible for load bearing as well as kinematic functions. However, the ankle joint is inherently more stable than the knee joint, which requires ligamentous and muscular restraints for stability. The ankle joint consists of the tibiotalar, fibulotalar, and distal tibiofibular articulations. The tibiotalar articulation is a hinge articulation between the spool-like convex surface of the trochlea of the talus and the concave distal surface of the tibia. Because it is a hinge joint it only allows flexion and extension movements of the foot in the sagittal plane. However, the other joints allow for inversion and eversion, inward and outward rotation, and pronation and supination.

Ankle integrity is improved by the medial and lateral collateral ligament systems, and the interosseus ligaments, as well as by all the muscles that cross the ankle (figure 2.6). The most important ankle flexors are the gastrocnemius and soleus muscles, both located on the posterior zone of the shank, possessing attachments to the posterior surface of the calcaneus via the Achilles tendon. The gastrocnemius is an important muscle in locomotion because it crosses both knee and ankle, having functions in both joints. In the knee, it helps with knee flexion and in the ankle, it is the main plantar flexor. The plantar extensors are the anterior muscles: the tibialis anterior, extensor digitorium longus, extensor hallucis longus, and peroneus tertius muscles. The peroneus longus and brevis have the primary role in eversion and inversion.

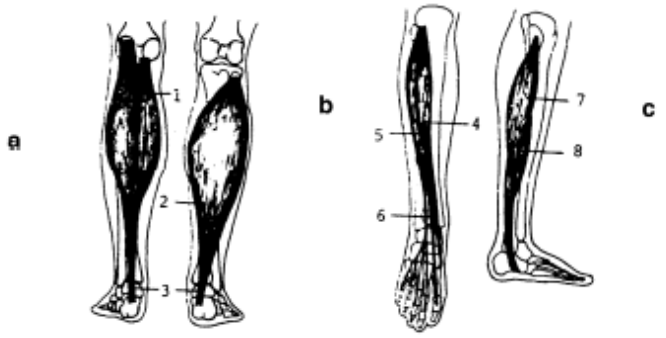

Figure 2.6: Ankle muscles (a) posterior, (b) anterior, and (c) lateral views: (1) gastrocnemius, (2) soleus, (3) Achilles tendon, (4) tibialis anterior, (5) extensor digitorum longus, (6) extensor hallucis longus, (7) peroneus longus, (8) peroneus brevis. (From [6])

Although more stable than the knee joint, the ankle joint responds poorly to small changes in its structure. Loss of kinematic and structural restraints due to severe sprains can seriously affect ankle stability and can produce malalignment of the ankle joint surfaces. Inversion sprains are the most common injuries, occurring when the body weight is placed on the ankle when in its inverted position [7] [12].

2.1.7. The Motor Unit

A given muscle's force power and endurance characteristics are determined by the distribution of slow and fast twitch motor units it possesses. In sprinters, lower leg muscles may consist of 75% fast motor units and 25% slow motor units, while for marathon runners the opposite is observed. However, in all of the muscles of the body, different relative distributions are observed, given that different muscles have different

functions throughout the body. There is also a genetic predisposition for certain motor unit distribution between individuals.

Motor unit is the designation given to the set of all muscle fibers activated by one motor neuron, sharing the same properties between them (figure 2.7). Muscles that need more power and perform forceful action are formed mainly by fast motor units, while muscles that are expected to perform endurance and postural tasks are composed mainly by slow motor units. The size of the motor units can differ depending on the functional properties of the muscles, (e.g., in our lower limb muscles a motor neuron can activate up to two thousand muscle fibers, while in eye muscles only a few muscle fibers are activated by a motor neuron) [13].

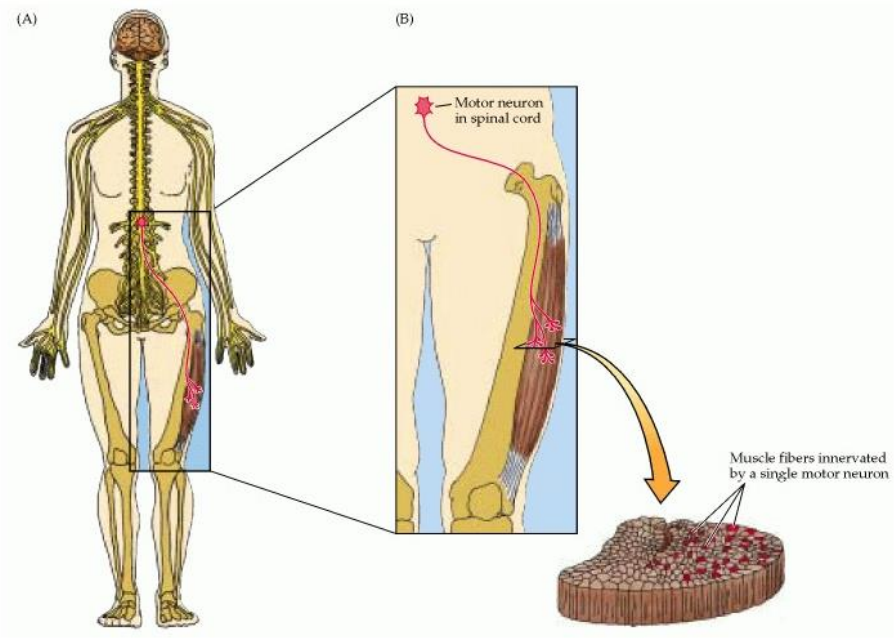

Figure 2.7: The motor unit. (A) Diagram showing a lower motor neuron in the spinal cord and the course of its axon to the muscle. (B) Each motor neuron synapses with multiple muscle fibers. Cross section through the muscle shows the distribution of muscle fibers (red dots) contacted by the motor neuron. (From [12])

When approached from an electrophysiological point of view, different types of motor units show different thresholds when recruited. Slow motor units have a lower threshold and, therefore, are recruited first, while fast motor units, that have higher thresholds, are recruited later as force development increases [14]. As a result, depending on the demands of certain muscular tasks, a specific set of motor units that better suits the tasks is involved. There are, however, some situations where full muscular actions are required, activating all muscle units. The different motor units show differences in their fatigue capacities, fast muscle units become exhausted quickly due to their enzyme profiles, whereas slow motor units act over long periods due to their high oxidative capacities [15].

Once recruited, a motor unit's firing frequency determines its force output. Fast motor units, in contrast to slow motor units, can be driven to a great increase in firing frequency, resulting in a fused tetanus. For fast and explosive muscular actions, the activation of motor units occurs in doublets, leading to a force increase and improved ability of the muscles to maintain high force during the prolonged contraction [16] [17].

2.1.8. The Sensory-Motor System

The force generating cross-bridge contraction cycle (i.e., muscle contraction cycle) is initiated by nerve impulses that arrive from motoneurons located at the spinal cord. The arrival of the impulse at the terminal axon causes the release of the neurotransmitter substance, acetylcholine (ACh), into the synaptic cleft bound by the receptors of the muscle fiber sarcolemma. If the amount of ACh surpasses a certain threshold, the membrane of the muscle fiber becomes depolarized over its entire length, also entering the tubules network inside the muscle cell. Calcium ions are released, and the cross-bridge cycle begins. Because they form a functional unit, the motoneuron and the muscle fiber are considered a motor unit. Coordination of human movement, however, is never based on a single muscle that produces force. A complex sensory-motor interaction is required to balance motion tasks around a single joint system. Therefore, every movement must be controlled by the central nervous system.

To understand how this interaction works, and how the central nervous system controls movement, we must focus not only on the motor system but also on the sensory system. Our sensory system provides information internally from our body, but it also provides information about our surroundings and external stimuli, therefore being essential to guide movement. Spindle afferents behave like passive stretch receptors, increasing their firing frequency during stretch and decreasing during shortening, in plain terms, they sense the length of the muscle. Therefore, when stretch forces applied to one muscle are detected by the muscle spindles, they propagate the information via primary afferents to the central nervous system [18]. When the excitation is high enough to surpass a certain threshold at the alpha-motoneuron, an efferent volley is released, which in turn leads to muscular contraction of the previously stretched muscle. We can observe that motor action directly depends on sensory information, and movement initiation can originate from the spinal level without involving higher centers. For that reason, a variety of different motor actions can be processed by the motor circuits in the spinal cord. Besides achieving control of muscle length, to stabilize posture for example, the nervous system has other objectives by using afferent input. Control mechanics that adequately modulate the gain of postural reflexes should include peripheral information to describe the influence of gravity as well as inputs from the muscle spindles and vestibular system. Mechanoreceptors in the joint capsules, joint ligaments, and skin, also provide sensory feedback to our nervous system. All these inputs allow for our naturally high adaptable reflex pattern [15]. However, with increase of movement complexity to the point it no longer functions as an automatic flow, control of motor activity is shifted to higher centers, such as the brain stem or cortical regions.

2.2. Mechanics

Now that we have discussed our locomotor system, its different joints, and the basic principles of how muscles contract or extend to move said joints, we can approach the fields of science that study these phenomena.

Mechanics is the branch of physics that is concerned with the motion and deformation of bodies that are acted upon by mechanical disturbances called forces [7]. Given that it is a branch of classical physics, it deals with bodies at rest or that are moving at a speed significantly lower than the speed of light. Because the motion of the mechanical system takes place in space and time, in mechanics, the notions of absolute space and absolute time are introduced. The notion of absolute time indicates a constantly changing quantity whose value always increases from past to future and it is assumed that this quantity is equal at all points

of matter. Absolute space denotes a three dimensional, homogenous, and isotropic Euclidian space. Therefore, we can say that one rigid body moves in relation to another if distances between certain bodies change in this space [19].

When studying the motion and deformation of bodies, it becomes important to categorize them. In general, a material can be described as either a solid or a fluid, with solid materials being described further as rigid or deformable. Even though some bodies are described as rigid, every object or material undergoes some deformation, how small it may be, when acted upon by external forces. We consider a body as rigid when the amount of deformation is so small that it does not affect the analysis in play, therefore carrying out the analysis with relatively simple computations.

The science of applying the principles of mechanics to analyze and design mechanical systems is called applied mechanics, and it can be divided into three main fields (figure 2.8): rigid body mechanics, which is focused on an idealization of a body that does not deform or change shape; deformable body mechanics, focused on the study of systems in which forces cause change in the dimensions of a body structure; and fluid mechanics, which is concerned with the study of the behavior of fluids (e.g., gases, liquids, blood, and plasmas) at rest and in motion [7]. In this dissertation, only the rigid body mechanics are of interest.

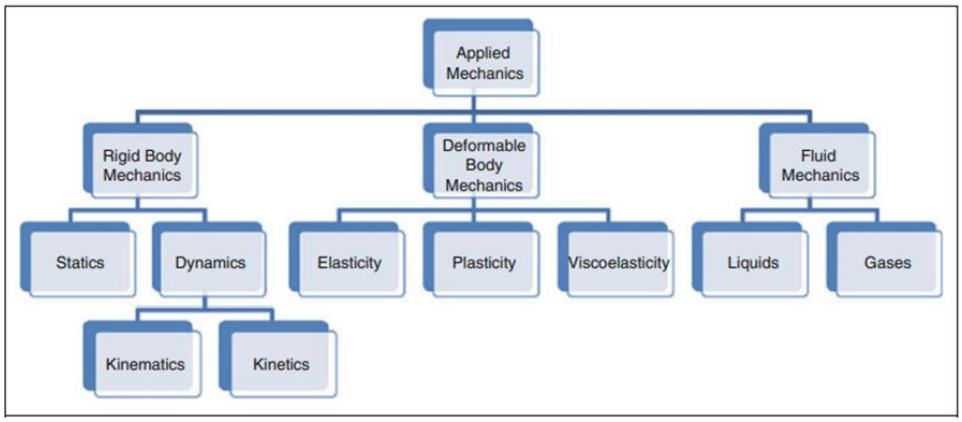

Figure 2.8: Classification of the subfields of applied mechanics. (From [6])

Statics is the branch of rigid body mechanics that deals with the study of forces on rigid bodies at rest or moving with a constant velocity, while Dynamics deals with bodies in motion. Kinematics is the branch of Dynamics that deals with the geometry and time-dependent aspects of motion without accounting for the forces causing the motion. On the other hand, Kinetics is based on Kinematics, but it includes the effects of forces and masses in the analysis. It is also of note that although the field of statics deals with the analysis of rigid bodies in equilibrium, analysis that deal with the deformation characteristics and strength of materials also start with static analysis.

2.2.1. Kinematics

Kinematics is the branch of Dynamics concerned with the description of geometric and time dependent aspects of motion, without reference to the forces which either cause the motion or are generated by the

motion. Kinematics is, therefore, defined as the "study of motion" or the "geometry of motion" [7] [15] [19] [20]. To investigate the geometrical properties of motion, in kinematics one introduces a certain rigid body that is fixed. The motion of the other bodies with respect to that body is called absolute motion [19]. The phenomena (i.e., motions) rather than the causes (i.e., forces) are the subject of analysis in a kinematic study. Kinematic quantities of interest include position and orientation of the segments, positions of the joints, and their time derivatives (linear and angular velocities and acceleration) [15]. The analysis are based on the relationship between displacement, velocity, and acceleration vectors [7]. The motion of a particle can be described in several ways, and the choice of the most convenient way depends a great deal on experience and on how the data is presented. If the particle is confined to a specific path, its motion is said to be constrained. If there are no physical guides, the motion is said to be unconstrained [20].

In kinematics only three units are of use: 1 m, 1 s, 1 rad, and all characteristics of motion (distance, displacement, speed, velocity, and acceleration) are described with the aid of these three units only [19]. In kinematics, distance is defined as the total length of the path followed while moving from one point to another, whereas displacement is the length of a straight line joining the starting point and the ending point of the movement. Distance is a scalar quantity and displacement a vector quantity. Speed and velocity are also different: while velocity corresponds to the rate of change in position with reference to time (displacement/time) and is a vector quantity, speed is defined as the distance covered per unit of time (distance/time) and is a scalar quantity. In kinematics, degrees of freedom are a common expression to describe the ability of an object to move in space. An unrestrained object, such as a ball, has six degrees of freedom (three related to translational motion and three related to rotational motion). The human hip joint, for example, allows for three degrees of freedom, because it enables the lower extremity to rotate about one axis and undergo angular motion in two planes [7].

To study the human body using kinematics, the human body can be considered as a linked segment system linked at the joints. This consideration simplifies analysis of the segment motions by reducing complex segment motions in two mutually independent motion components: translation of the center of mass of the segment and rotation of the segment about its center of mass. A segment rarely shows complete translation or complete rotation, but a combination of both. In addition, given that the joint motions are the building blocks of the whole body motion, we may decompose the whole body motion in individual joint motions. The type of joint has influence in the type of segment motions observable [15].

2.2.2. Biomechanics

The international community adopted the term "biomechanics" during the early 1970s to describe the science involving the study of mechanical aspects of living organisms, normally of humans, but also of other beings. Biomechanics combines the field of engineering mechanics with the fields of biology, physiology, and kinesiology. In biomechanics, the principles of mechanics are applied to the conception, design, development, and analysis of equipment and systems in biology, medicine, and sports science. In its essence, biomechanics is a multidisciplinary science concerned with the application of mechanical principles to the human body in motion and in rest, whether it is by studying internal forces produced by the muscles or the external forces that act upon the body [7] [21].

The development of the branch of biomechanics has improved our understanding of normal and pathological situations, mechanics of neuromuscular control, mechanics of blood flow in the

microcirculation, mechanics of air flow in the lungs, and mechanics of growth and form, greatly contributing to the development of medical diagnostic and treatment procedures. It has provided the necessary information and analysis for designing and manufacturing medical equipment, devices, and instruments, assistive technology devices for people with disabilities, and artificial replacements and implants. It also constantly provides the means for improving human performance in the workplace and in athletic competition [7].

Different applied mechanics concepts and methods are applied in different aspects of biomechanics. The principles of statics can be applied to determine the magnitude and nature of forces involved in various joints and muscles of the musculoskeletal system, while principles of dynamics can be utilized for motion description and have many applications in sports mechanics [7].

2.3. Electromyography

Electromyography is the discipline that deals with the detection and analysis of the electrical signal that emanates from contracting muscles [22]. EMG is typically used to fractionate a body's response process as well as get timing of neural control and coordination among muscles groups, allowing the assessments of technical skills which, in turn, provide foundational information for motor skill analysis [23]. The signal described by an EMG is the electrical manifestation of neuromuscular activation linked with a muscle in contraction. The signal represents the current generated by the ionic flow across the membrane of the muscle fibers that propagates through the intervening tissues to reach the detection surface of an electrode. As we discussed before, the continuously repeated activation of muscle motor units will generate action potential trains. These action potential trains from active motor unit simultaneously active superimpose together to form the EMG signal. As excitation from the central nervous system increases to generate greater force in the muscle, a greater number of motor units is recruited and the firing rate of all active motor units increases [22], as seen in figure 2.9.

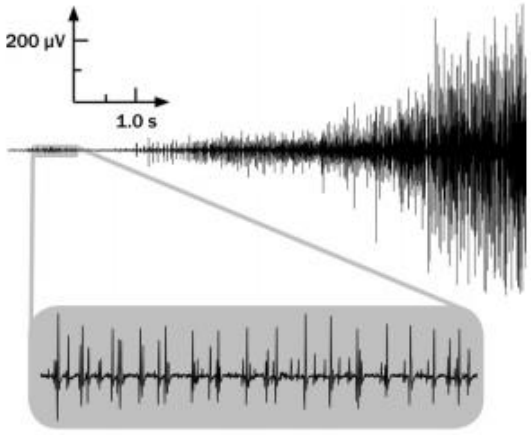

Figure 2.9: Increase of amplitude of an EMG signal as the force produced by the muscle increases. The signal corresponds to a recording with surface electrodes of the first dorsal interosseous muscle in the hand. (From [21])

Although the usage of motor unit action potential (MUAP) shape analysis is common practice, interpretation of the results is not simple and relies heavily on the experience of the observer. The electrical manifestation of a MUAP is accompanied by a contractile twitch of the muscle fibers, which, to sustain a

muscle contraction, must be activated repeatedly. That sequence is the motor unit action potential train (MUAPT). The waveform of the MUAPs within a MUAPT remains constant if the relationship between the electrode, that is collecting the data, and the muscle fibers remains constant, if the properties of the electrode do not change, and if there are no biological changes in the muscle tissue.

2.3.1. Electrodes and Recording of the EMG Signal

EMG activity can be recorded using either monopolar or bipolar recording arrangements. In monopolar, an electrode is placed directly over the muscle and a second electrode is placed at an electrically neutral site. Monopolar signals tend to yield lower frequency responses and less selectivity than bipolar recordings. Although monopolar recordings are frequently used during static contractions, they are less stable and are a poor choice for nonisometric contraction measurements. Bipolar recordings are more common. Two electrodes are placed in the muscle or on the skin overlying the muscle, and a third neutral, or ground, electrode is placed in an electrically neutral site. This configuration records the electrical difference between the two recording electrodes, attenuating signals that are common between them. It is typical to exist radio frequency and line activity from electrical outlets or lights, or in the environment. The use of a bipolar setting helps greatly reduce their signals. If the amplitude of the EMG signal exceeds the amplifier's gain, it becomes saturated, clipping the signal, resulting in loss of potentially valuable information [24]. Two types of electrodes are used to detect the EMG signal: surface electrodes and inserted (wire or needle) electrodes [25] (Figure 2.10).

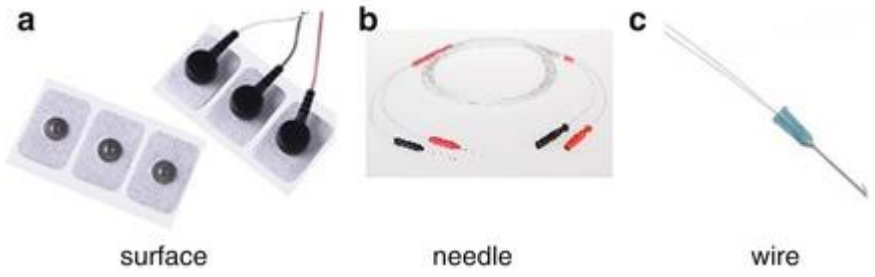

Figure 2.10: EMG electrode types: (a) surface electrodes, (b) needle electrodes, and (c) wire electrodes. (From [24])

2.3.1.1. Surface electrodes

Surface electrodes can be passive or active. Passive electrodes consist of a conductive detection surface that can detect the current on the skin through its skin-electrode interface. Active electrodes, on the other hand, contain a high input impedance electronics amplifier in the same housing as the detection electrodes, rendering it less sensitive to impedance of the skin-electrode interface. The most common form of passive electrode consists of silver disks that adhere to the skin, generally with the use of conductive gel or paste between the electrode and the skin to improve electrical contact. The impedance can be further diminished by removing dead skin or body hair, in case it is present. The lack of chemical equilibrium sets up a polarization potential that can vary with temperature, sweat accumulation, changes in electrolyte concentration of the gel, relative movement of the skin or the electrode, as well as the amount of current flowing into the electrode. Active surface electrodes were designed to be "dry" electrodes, eliminating the need to prepare the skin for application and eliminating the need for a conductive medium. These electrodes

may be resistively or capacitively coupled to the skin. Capacitively coupled electrodes have the advantage of not requiring a conductive medium but have higher inherent noise level. Active surface electrodes also do not have long term reliability because their dielectric properties can change with the presence of perspiration and the erosion of the dielectric substance. The disadvantages of surface electrodes are that they can only be used effectively with superficial muscles, cannot detect selective signal from smaller muscles, and "cross-talk" signals from adjacent muscles become a problem. However, several circumstances call for the use of surface electrodes. They are the primary choice when representation of the EMG signal corresponding to a large part of a muscle is required; in motor behavior studies, when the time of muscle activation and magnitude of the signal are important; in psychophysiological studies of general gross relaxation of tenseness, such as biofeedback research; in the detection of EMG signals for the purpose of controlling devices, such as prostheses or aids for disabled population; in clinical environments, such as physical therapy and sports medicine; when simultaneous activity is being studied between muscles, such as the lower limb during walking; and in studies where the patient objects to needle insertions [22] [26] [27].

2.3.1.2. Needle electrodes

The "concentric" electrode is the most common needle electrode used by clinicians. In a monopolar configuration it contains one insulated wire in the cannula. The tip of the wire is not covered and acts as a detection surface. In a bipolar configuration it contains a second wire in the cannula and provides a second detection surface. The needle electrodes provide two main advantages. Firstly, its small pickup area enables the electrode to detect individual MUAPs during low force contraction. Secondly, the electrodes may be repositioned within the muscles, after insertion, so that new tissue can be explored or for the signal to be improved. The electrode itself consists of a thin, stiff, sharpened metal filament, usually made of tungsten. Because it is so thin, it can detect the action potentials of individual fibers. Due to its characteristics, it has been proven to be very useful for neurological examinations of denervated muscles [22] [28].

2.3.1.3. Wire Electrodes

Wire electrodes can be made from any small diameter, highly nonoxidizing, stiff wire with insulation. Platinum, silver, nickel, and chromium alloys are typically used for the wires, and nylon, polyurethane, and Teflon are typically used as insulation. The most preferable alloy is 90% platinum and 10% iridium, as it offers a good combination of chemical inertness, mechanical strength, stiffness, and economy. The electrode is built by inserting two insulated fine wires (25-100 mm diameter) through the cannula of a hypodermic needle. The distal tips of the wire are not insulated and bent to form two staggered hooks. The electrode is placed in the muscle by inserting the hypodermic needle and the withdrawing it, with the wires remaining lodged in the muscle's tissues. They can be removed by gently pulling them out, because they are so pliable the hooks straighten upon retraction. When the purpose of the study is to record a signal that is proportional to the muscle contraction, repositioning the electrode is not important, so wire electrodes are not necessary. However, for applications such as recording distinguishable MUAPTs, this limitation is counterproductive. Another limitation is that with the first muscle contractions after insertion the electrodes tend to move from the spot that is meant to be researched [22] [29].

It is important to note that researchers in biomechanics are usually interested in detecting the electrical activity of a large portion of the muscle, rather than a few muscle fibers. For that reason, surface EMG is the most common in biomechanical studies as it is usually used as an indicator of gross muscle activity [15].

2.3.1.4. Electrode Placement

When choosing the location of the electrode placement, signal/noise ratio, signal stability, and cross-talk from adjacent muscles must be considered. The stability addresses the issue of the modulation of the signal amplitude due to relative movement of the fibers with respect to the detection surface of the electrodes. The issue of cross-talk concerns the detection of signals originating from different muscles, which is an issue mainly of surface electrodes. It is also important to take into account the shape of the muscle, as both the innervation zone and the tendon muscle tissue interface alter the characteristics of the EMG signal [22].

When collecting surface EMG data, electrode placement over the muscle and interelectrode distance are important factors. The three most common electrode locations are: over the motor point of the muscle, over the belly of the muscle, and midway between the innervation zone and tendonous regions. Placing the electrodes over the motor point or belly of the muscle maximizes EMG amplitude. In terms of interelectrode distance, the two primary factors to be considered are the pick-up area and bandwidth. Since most of the energy in surface EMG signal originates from muscle fibers located within 0.4 length units (one length unit = interelectrode distance) of the recording electrodes, so, smaller interelectrode distance results in smaller pick-up areas [30]. Therefore, larger electrode distances also result in longer wavelengths, resulting in lower frequency EMG signals [15].

2.3.2. BITalino

BITalino is an electronic kit that offers physiological sensors for application in areas of electrocardiography, electromyography, electrodermal activity, sports, and more. The signals collected by this device can then be consulted and stored in a purpose-built application, OpenSignals [31]. The hardware consists of a modular device, allowing for the addition or removal of components of the particular set you try to build. This way, various sensor modules can be organized according to the needs of each type of user. The user can build a low-cost toolkit for learning or prototyping biosignal-based applications, or a well-tested wearable platform for biomedical research [32] [33]. The data is analyzed in the OpenSignals software. The main purpose of this platform is real time data visualization.

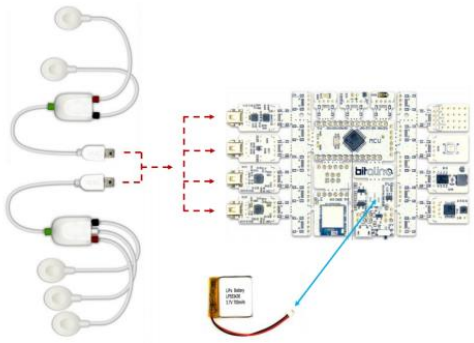

Figure 2.11: Example of a BITalino setup: BITalino Board Kit on the right, electrode cables on the left with insertion according with the red lines, and battery connection in blue. (From [32])

2.4. Biomechanics in Football Free Kicks

Scientific research in the field of sports is nothing new, it has been around since its conception. From running the marathon in sandals to the use of specialized shoes and insoles, from the initial formula 1 cars to the modern pieces of machinery we have today, from playing football with a ball made of animal bladders to playing with a rubber and leather ball. Sports evolve and that is a very exciting premise to both fans and players. Football as the most played and watched sport in the world would be expected to lead this wave of innovation. However, scientific research on football and their performance variables are not proportional to its popularity. Obviously, there has been a lot of changes in football since its conception, but the study of the game and of ways to achieve a competitive advantage over your opponents is ongoing and will be as long as teams wish to improve and win.

Biomechanical techniques can be utilized to define the characteristics of skills within a sport, in this case football, to acquire a better understanding of how effective the mechanical executions of certain movements are, helping the identification of parameters involved in their successful performance. With this information we can improve different aspects of these skills, through planning, practice and in-game execution [34].

In terms of researched skills, even the most basic (i.e., kicking and passing) have been under-researched, although most biomechanical studies in football have been directed to kicking, mainly the maximal instep kick. The lack of studies cannot be solely attributed to reduced interest or availability in the researchers' side, given that football is a team sport with a substantial number of different skills being executed in several different situations, resulting in the influence of the specific game on these skills, making even the kicking context difficult to define in a simple to research way. Additionally, it becomes difficult to collect unconstrained data. It can be collected in the same environment where the games are played and the players are accustomed to, if the researcher is prepared to lose the safety of a controlled test space, complicating therefore a clean acquisition of data, or it can be collected in a laboratory, resulting in data that has less noise and is more easily collected. However, the ecological validity of that research will be much lower, because it will not represent results that are as accurate in regards to the real-world settings it is meant to translate. This is why researchers have been forced to make assumptions and simplifications in the hope of figuring out the main factors for the improvement of specific skills [35] [36].

To make assumptions and simplifications, regular actions have to be found in the game that are of easier study. It is known that around one third of all goals in major leagues are scored from set plays (corners, direct free kicks and indirect free kicks) [3] [37], which results in a need for preparation and planning of

set plays on both sides, offensive and defensive, if a team is to succeed in their league [38]. From the beginning of the century it has been reported, in men's domestic and international football, an increase in set play efficiency, with better ranked teams scoring not only more set play goals but being more efficient with their opportunities [39] [40]. Direct Free Kicks are the most effective of the set plays, their potential for goal is largely dependent on the location where it is performed from, influencing the number of players in the wall, distance, angle, and the positioning of other players.

In a game there are about 6 Free Kicks that are closer than 35 meters to the goal, which should be the only ones to be relevant for goals. In a sample (n=2681) examined by Link et al [41], 22.2% of Free Kicks are played as shots (Figure 2.11), while the remaining Free Kicks are crossed or brought the ball back to play via a pass in an equal proportion. Shots are generally taken from a frontal position, while on the sides of the pitch only about 10% of Free Kicks are performed as shots. The ratio of goals scored from Free Kicks was of 7.6%. 4.1% of all goals resulted from Free Kicks played as a shot. Other studies show scoring rates of 1.1% for open play crosses and 2.3% for indirect Free Kicks [37] [42].

Indicator	%
TYPE OF PLAY	
Shot at goal	22.2
Cross	38.3
Pass	39.5
OUTCOME SHOT	
Goa	7.6
Border	2.8
Saved	27.7
Off target	31.7
Block	24.5
Block outside	5.6
OUTCOME CROSS	
Shot at goal	15.5
Flick-on	5.1
No control	7.8
Opponent	70.5
Block	1.0

Figure 2.12 - Quantitative distribution of categories of type of play, outcome shot and outcome cross (n = 2681 free kicks within 35 m to the goal) (from [41])

Chances of success, regarding shots on goal, increase for high velocity shots [41] as well as for shots placed near the goalpost, farthest away from the keeper [43]. It becomes harder to reach conclusions regarding crosses, correlations between positioning and scoring could not be found. However, one study has shown that crosses directed towards the center of the penalty spot or in front of the goal posts show increased chances of scoring [44].

Therefore, one common denominator in most of the studies performed, is the analysis of the kick of a stationary ball, specifically of a Free Kick performed as a shot on goal, given that it is a particularly important part of the game, in addition to the fact that the study of kicking a moving ball would represent an immensely greater challenge. Studies mainly focus on two areas: biomechanical variables, such as joint velocities and accelerations, angles and distances; or the capture of electromyographic data, both of which will be present in this dissertation. Data collection of biomechanical variables has been performed with cameras ranging from 64 to 200 frame/s and focused mainly on the lower body, specifically on the kicking

leg. It comes as no surprise then that most results are of sagittal plane biomechanical parameters: last stride length, joint velocities, joint angles, joint positional changes and ball speed. There is, however, a few parameters that do not come from the sagittal plane, such as the angle of approach to the ball that the player uses. The study of the stationary ball kick mainly takes the form of Free Kick studies. To perform a Free Kick a player starts running towards the ball from a distance of 3 to 5 steps and from an angled position. Then the supporting foot is placed slightly to the side of the ball, the kicking leg is taken backwards with the leg flexing at the knee. The forward swing is performed in a whip-like manner initiated by the rotation of the pelvis around the supporting leg and by forward movement of the thigh of the kicking leg. The thigh begins to decelerate after this action has taken place, during which the shank extends forward being at almost full extension at ball contact. The leg remains straight, only beginning to flex during the follow-through [34] [35]. In most of the studies, ball speed is used as a measure of success, therefore it is to be expected that with age and improved muscle strength the performance of the players also improves.

2.4.1. Joint and Ball Velocities

As previously stated, there are several biomechanical parameters to consider when discussing the performance of a Free Kick. Joint and ball velocities are possibly the parameters that have been researched more deeply in the field. Ball velocity is considered the main biomechanical indicator of Free Kick success [45] [46], however, it is the final product of a complex movement, out of which a lot of information may be of use. For us, foot, knee and hip velocities (and displacements), will also be of significant importance, since they provide us with a better understanding of the role of each biomechanical segment in the final output of the movement. Clearly the foot raises its speed abruptly until the impact with the ball, while the knee and hip show slower top speeds, reaching their maximal speeds at the midway point of the movement and in the beginning of the movement respectively, which gives a biomechanical view to the whip-like movement described previously, as seen on figure 2.13. Besides the biomechanical segments that influence ball speed, various factors combine to create the final result: technique [34] is trained for most of pro athletes lives resulting in different skill-levels [5] [47], which explains why different players can show very different Free Kick performances; approach angle and speed [48], foot-ball impact [49] and type of kick [50] have a direct impact on the trajectory and speed of the ball as it exits the foot,; gender [51], age [52], limb dominance [53] [54] and muscle strength [51] [55] [56] provide useful information on why certain body types and musculatures allow for a better biomechanical performance. All of these factors help explain a wide range of ball speed values as well as the joint speeds. It is also of note that ball speed values calculated in a competition setting are greater than those found under a laboratory setting.

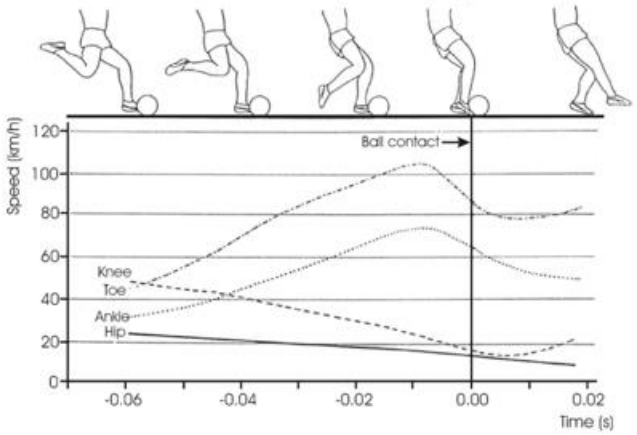

Figure 2.13: Hip, knee, ankle, and tow velocity during the kicking motion of a Free Kick. (From [34])

Free Kicks can be taken in a stationary manner, where the player does not run towards the ball, or they can be performed in a running manner. Given that most of the Free Kicks are performed with a running approach, that is the setting that was researched in this dissertation. Maximal speeds of the kicking foot when performing a Free Kick are generally between 20 to 28 $m.s^{-1}$ [34], while ball speed values can range from 28 to 33 $m.s^{-1}$ [57] [23] [58]. As is easily observed, the ball-to-foot speed ratio is greater than one. This ratio can be a great indicator of a higher level of skill if a player produces more speed on the ball from a slower foot speed [59]. However, this ratio provides a larger amount of information than only the skill level of a player.

2.4.2. Ball-to-Foot Speed Ratio

Ball-to-Foot Speed Ratio is, as previously stated, a particularly important parameter in the biomechanical analysis of Free Kicks. It is, however, of accentuated importance for this dissertation given that, with the use of a single camera (which is our case), it is not viable to ascertain both foot and ball speed simultaneously Therefore, the ratio allows for a better understanding of the quality of one of the parameters, in the case it is not in perceptible view to be acquired in the data collection.

Ball-to-Foot Speed Ratios have been reported in a range from 1.06 to 1.29, with very acceptable correlation coefficients ($r > 0.74$) [53] [59] [60], when regarding instep kicks, kicks performed with the top of their foot to provide maximum power to the ball [61], the higher the speed of the foot before ball impact, the shorter the contact between foot and ball will be resulting in a higher ball speed [53]. No such ratio is found for kicks performed with the inside of the foot, probably due to it being a much more accuracy and curve focused kick than the instep kick [62]. As foot velocity is the best determinant of ball speed, slower ball speeds in certain kicks may not only be caused by slower foot speeds using the same type of kicking performance but because a different kicking motion was implemented causing said lower speeds. However, kicking motion is not the only factor to be cautious about when discussing ball-to-foot speed ratios, since upon the interpretation of these results, it is often unclear which part of the foot is being used to calculate the speed values [34], resulting in very different ratios when utilizing the ankle speed or the toes speed, for example, being of upmost importance to define clearly before any trials begin which zone of the foot should be tracked and calculated.

2.4.3. Approach Factors

The approach towards the ball can be one of the most important aspects of the kick. Different players prefer to approach the ball in different manners: some take fewer to no steps towards it while others take several, some prefer to engage the ball directly in a 0° angle while others engage it in a completely perpendicular way. The question becomes: is there an approach type that provides maximal ball speed?

To simplify the approach movement, we can divide it in the approach angle and the last stride length. The last stride length corresponds to the length between the toes of the dominant foot at the moment it leaves the ground to perform the kick and the heel of the support leg as it lands at the side of the ball to provide support to the body as the kicking motion is underway. The previous steps leading to the kick provide the body more speed and, consequently, more foot speed. The length of the final step enables the pelvis to be rotated backwards, the longer the length of the step, the greater the range of motion of the rotation. The extra distance the foot travels, due to the greater range of motion, allows for an increase in acceleration of the foot towards the ball, by initially increasing the thigh's acceleration, which continues its movement until it approaches a vertical orientation. At that moment it abruptly decreases its speed, while the shank accelerates in the previously stated whip-like movement, therefore providing a greater maximal foot velocity in exchange for a longer last stride [63] [64].

The angle of approach to the ball has been a better researched aspect of the ball approach. This angled approach allows the body to be orientated in a way that facilitates the pelvic rotation previously mentioned [64]. However, different angles can be utilized when kicking the ball. In 1988, Isokawa [48] attempted to investigate the differences between different approach angles (0, 15, 30, 45, 60 and 90°) in the direction of the ball, with 0° being the direct approach to the ball. Isokawa concluded that the shank achieved maximum velocity at a 30° angle while the maximum ball speed was achieved with an approach angle of 45°, with these results being corroborated in later research [64] [65] [66]. An approach angle between 30 to 45°, would therefore, appear to be the optimal range for the performance of Free Kicks, which would appear to be in agreement with the players choice in game [48] [65]. One explanation for this could be that an angled approach enables the leg to be inclined towards a frontal plane, allowing the foot to be placed under the ball with ease, improving the contact between foot and ball [48].

It is interesting to note that Free Kicks are not always performed at an equal distance to the goal or on the same side of the pitch. While research can be found in a general manner regarding the approach to the ball in a Free Kick (and of the biomechanics of the Free Kick in itself), slim to no information exists regarding the influence of pitch zone in the Free Kick. One study [67] found that, when performing a longer range kick, professional players performed a longer last stride and showed a greater pelvic rotation amplitude, but this has not been researched in a more detailed manner since. In this dissertation we found it important to attempt to provide more information regarding this factor.

2.4.4. Individual Factors

In contrast with the approach factors, individual factors are, in a certain way, more specific to the player, being dependent on their height, weight, and size in general. There are two characteristics that are of specific interest for us: firstly, the support leg angle upon ball impact, which is one of the parameters measured in

this dissertation that allows us, within a certain range, to ascertain the preferred way of a player to perform the Free kick; secondly, the muscle strength of the players, which serves as an explanation for greater speed values for certain players when comparing with players with different body musculature.

As opposed to the approach angle, which modifies the players maximal foot speed, the support leg angle's most vital objective is to absorb the impact the kicking motion causes. Extremely few articles or books have focused on this parameter so far, but there is some evidence that the support leg may be flexed at an angle of around 26° at the moment the support foot hits the ground, remaining in a flexed state through the movement reaching an angle of around 42° upon ball contact [65]. Because it is responsible for absorbing the impact it is the reason the forward motion slows down after the ball contact.

When comparing male players to female players or when comparing different age groups of players, it has been clear that greater ball speeds have been produced by the male players or by the older players. The most basic explanation for this difference is their greater muscle strength, which in several studies has been measured on isokinetic dynamometers [51] [65] [68].

Foot and ball speeds have been found to show a moderately high correlation with age ($r = 0.68$). One of the reasons for this, is the higher number of hours of training that come with age, but it is also related to the increased muscle strength in the lower limbs that develops in our teenage and young adulthood years. From the age groups between the age of 9 to 15 there is significant increase in ball speed (from 15.2% to 21.4%) and foot speed (from 7.7% to 14.3%) values begin stabilizing after this age. These results show that, as previously stated, foot velocity is not the only explainer for an increase ball speed. Training is, therefore, the main focus for a player if he hopes to improve his Free Kick performance [52]. Training can be double faceted, players can practice their technique to improve, but they should also do power focused training with focus on their lower limbs. In young adults, short-term training of ten weeks has been sufficient to improve kicking performance [69], however, in adults a longer period is needed to show significant results. In adults, different workouts have been implemented showing different results, with one aspect in common in their final product: they improve performance. As early as a study in 1988 [56], over a season of specific muscle strength training resulted in an increase of 25% in muscle strength and 4% in kick distance, with the correlations between muscle strength and kick distance improving until the end of the season. They noted that, even though muscle strength is only one of the factors in Free Kick performance, it is necessary for the continuous development of neuromuscular control of the movement. There have also been other forms of training applied, such as the stretch-shortening cycle strength training that has shown increases in concentric hip flexors and eccentric hip extensors strength, eccentric hamstring strength (77%), and in concentric quadriceps strength (25%), with muscle power tests (long jump, vertical jump, and single-legged triple jump) showing significant correlation with kick distance. It is reasonable to conclude that muscle training should be added to every player's football training if their objective is to improve their kick performance.

2.4.5. Accuracy Speed Differences

When analyzing the biomechanical parameters of the Free Kick we would expect maximum foot velocity when the foot hits the ball, given that we know that the greater the foot speed the greater the ball speed. However, some research has shown the contrary. Instead of the peak velocity in ball contact, it has been showed to be maximal instants before the contact itself [34] [70] [71], as seen in the previous figure 2.13.

When we look at the Free Kick motion before the contact with the ball, the thigh begins to decelerate, however this results in an acceleration of the shank contradicting the findings of these studies. Deceleration before impact is not unheard of. For example, in tennis training this phenomenon has been reported upon the racket's impact with the tennis ball, in which researchers attributed this finding to a preparation of the body for the force of impact [72] However, a football kick impact is not nearly as impactful as in tennis, seeing as the football is extremely light and, consequently, caused minimal reactive force on a heavier body segment such as the leg [73].

The reasons for these results in some studies can only be speculated, with insufficient quality of data acquisition being one of them. However, with the number of studies that show these findings, more biomechanical focused explanations were given. The most common and more accepted one is that the slight deceleration of the foot can be interpreted as a motor control strategy to improve the accuracy of the Free Kick [73], abdicating a small amount of velocity for extra accuracy. In this dissertation, we expect the Free Kicks to be performed mainly with an instep kick technique. If a slight deceleration is found, the question becomes: Is it performed on purpose by the player or is it subconscious?

Interestingly, several studies show the inverse of these findings with peak velocity recorded upon ball impact. Nunome and colleagues [53] go as far as to say that the decelerations of the kicking leg reported in previous studies are due to inadequate data filtering methods, as opposed to a method to enhance accuracy. However, we believe that one interesting aspect has to be taken into account: when a kick is performed with the objective of giving a curved trajectory to the ball, the ball must be kicked off-center to produce spin trading of the peak velocity for increased spin [49]. So, the reason for the deceleration, if it exists, may be due to the performance of a different type of kick and not due to a desire to enhance accuracy by itself [74].

Accuracy is a parameter that, by itself, is already very dependent on the type of kick performed and what the target of the kick is. A faster kick is usually less accurate, with the increase of speed there is loss of vertical accuracy both when the target is on the ground with the kicks likely to land 50 cm above ground with some passing over the crossbar, or when the target is in the air, where even slow kicks are vertically inaccurate. Horizontal accuracy was also almost inexistant regarding fast kicks. Regardless of the speed, kicks performed with laces (i.e., instep kick) were less accurate than the kicks performed with the side of the foot [62].

2.4.6. Electromyography in Biomechanics

The use of EMG in biomechanical studies has usually two goals: to describe the activity of selected muscles for skill optimization and learning or training, and to determine loading intensity during performance for injury prevention [70] [75] [76]. It has been used to examine muscle activation patterns to explain the role of muscle contraction during the kick, quantifying the leg muscles' activation to confirm and coordinate with the whiplike movement [56] [70] [75] [76] [77]. As expected, studies have shown higher muscle loading in the kicking leg when compared with the non-kicking leg in the iliacus, vastus medialis, gastrocnemius, and hip adductors. Also, as expected, given that EMG can be used to quantify the neuro-muscular control or coordination of muscles in a movement, kicks intended for different targets have shown different EMG readings [78]. Interestingly, kicks steered towards the right, produced significantly greater muscle activity than those towards the left, with the higher quadricep EMG recorded in kicks towards the top right corner.

In literature, large variations in EMG magnitude and temporal patterns have been recorded, preventing the extraction of safe conclusions regarding the role of various muscles during the kick [45]. Strangely, it appears that joint and segmental movements during the kick are driven by simultaneous activation of many muscles, with several of these muscles producing moments around the joint in opposing directions (antagonists) [57] [70]. This is sometimes defined as the "soccer paradox" [56] because the higher the simultaneous activity of antagonist muscles, the lower the net moment produced around the joint and less powerful the resulting action is. If both agonist and antagonist muscles contract simultaneously, they produce opposing forces on the joint, enhancing the stability of the joint, but turning the movement more inefficient [45]. Given that the main aim of the kicking action is to produce the highest ball speed, then one could suggest that antagonist activity at the end of the movement is a limiting factor. However, the lack of speed and increase of stability can improve accuracy and lessen the chances for injury. In a martial arts study [57], two observations regarding this topic are worth taking into account. Firstly, thigh acceleration was accompanied by considerable levels of rectus femoris (flexor) and hamstring (extensor) activation captured by EMG, as well as a high motion-dependent moment from the shank. Secondly, shank acceleration was accompanied by a high muscular activity of the knee extensors, whereas when the shank decelerates this activity is decreased and the hamstring and gastrocnemius activity increased. It was then proposed that the thigh deceleration is mainly caused by an interactive moment exerted by the shank rather than a hip extension or flexion moment, with the extensor and flexor muscles having a compensatory role in the deceleration. Using surface EMG electrodes hip and knee have shown maximal activity during the terminal part of the backswing and also prior to the ball impact [56]. Needle electrodes were compared with surface electrodes, showing that surface electrodes' EMG activity were higher for all muscles throughout the kick, but proximal-to-distal sequence of muscle activation was not evident [45]. It has been shown that kicking speed is significantly higher when the knee extensor musculature is stretched and then shortened, when compared with kicks revolving only around concentric actions [79]. Therefore, the role of the stretch-shortening cycle of the knee extensors has been emphasized for a successful kick [34]. Temporal EMG characteristics do not differ between expert or young subjects' kicking patterns, meaning that it is mainly the magnitude rather than the sequence of muscle activity that characterizes football kicks by more skillful players [80].

The significant power spectrum of EMG signals ranges from approximately 20-500 Hz, while low-frequency noise, such as movement artifacts, occurs predominantly in the range of 0-20 Hz. Therefore, several publications have suggested optimal cutoff frequencies for EMG bandpass filtering for conductive EMG sensors to be around this 5-30 Hz on the lower range and 400-500 Hz on the higher range [81] [82] [83] [84].

3. Materials and Methods

The work performed in this thesis was twofold. Firstly, with the support of one club of the Portuguese first division, a data collection of Free Kick parameters was performed with the use of the Wyscout software, considering 3000 Free Kicks from a distance of 40 meters or less to the goal line from the 18/19, 19/20, and partially the 20/21 season of the Liga Portugal 2 (Portuguese second division of football). Based on the data collected in this first phase, a protocol could be put in place to perform our second phase. The second phase took place at one of the most highly regarded Portuguese football teams' football academy, and consisted of a biomechanical analysis of Free Kicks performed from specific pitch locations by young players of the under-23 football team, as well as from their B, which plays in the Portuguese second division. This biomechanical analysis consisted in filming the performance of the Free Kicks to later analyze kinematic parameters with the use of the Kinovea software, such as velocity, distance, and angles, while simultaneously recording EMG data from the movement. It is important to note that due to the pandemic, every aspect of this thesis that required interaction with players or managers was done so with the use of face masks and all the possible safety protocols.

3.1. General Free Kick Data Collection

The analyzed Free Kick general parameters in this project were obtained with the use of the Wyscout software. Wyscout is one of the most used technologies for scouting and for performance analysis in football, with over 600 competitions worldwide with data and video coverage. A team, a player, or a match can be the focus of the analysis. We focused on match analysis, that could be done by analyzing a full video of a match, the effective time of play, the goals, the highlights, or even more parameter focused settings as we can see in figure 3.1 [85]. As we began our analysis, we noted that only when analyzing the full game (or the effective time of play, when available), all the Free Kicks were shown, given that on the highlights or specific free kick setting some of the unsuccessful free kicks were not shown Therefore, as our objective in this phase was to create a truthful database of Free Kick information in the Portuguese Second Division, all matches were analyzed in full length, in three times the speed, until a Free Kick occurred, at which time the video would be stopped and slowed to allow for the collection of the data of the parameters. This was done for 3000 Free Kicks, since no previous work done on this field had a sufficiently large sample group (besides Link's et al [41] study, which analyzed ~2600).

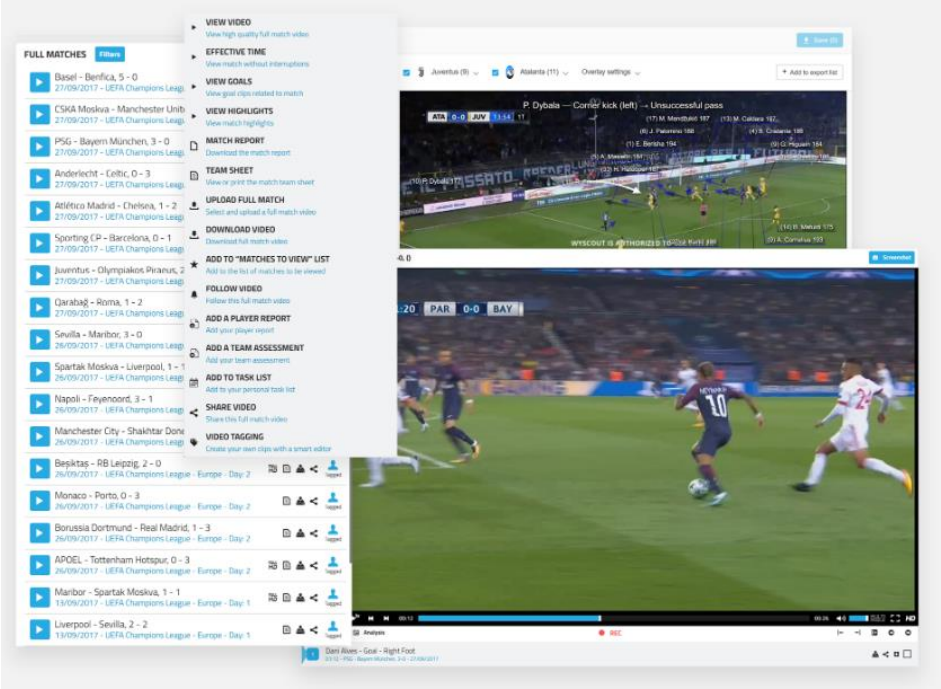

Figure 3.1: Wyscout match analysis options. (From [85])

3.1.1. General Free Kick Data Collection Parameters

All the parameters of the Free Kick data were placed on an Excel sheet, where the data was divided in the following parameters, shown in figure 3.2:

a) Freekick number, which denominated each Free kick from one to 3000;
b) Season, which indicated from what season the Free Kick was from, ranging from the 18/19 season to the 20/21 season;
c) Time, which placed the Free Kick at the minute of its performance in the game;
d) Attacking Club, meaning the team on offense ate the moment of the Free kick (n=24);
e) Defending Club, meaning the opposite, the team on defense at the moment of the Free Kick (n=24);
f) Field Zone, indicating in which of the ten zones, in which we have divided the pitch (figure 3.3), the Free Kick was taken: LF – Left Far zone (n=626), LN – Left Near zone (n=153), RF – Right Far zone (n=669), RN – Right Near zone (n=182), CLF – Center Left Far zone (n=337), CLN – Center Left Near zone (n=211), CMF – Center Middle Far zone (n=168), CMN – Center Middle Near zone (n=99), CRF – Center Right Far zone (n=357), and CRN – Center Right Near zone (n=198);
g) Shooting Foot, if the player that performs the Free Kick uses his right (n=1681) or left foot (n=1316);
h) People on the Wall, indicating the amount of people forming the wall between the ball and the goal, possibly being 0 (n=54), 1 (n=1535), 2 (n=819), 3 (n=190), 4 (n=175), 5 (n=137), 6 (n=73), 7 (n=13), or 8 (n=3);
i) Free Kick Type, which divides the data between shots (n=622), crosses (n=2187), or passes (n=191);

j) Direction of Cross, of Shot, or of Pass, dividing the data between crosses directed to the 1st post (n=534), center of the area (n=822), 2nd post (n=711), or the front of the area (n=127), between shots directed at Top Left (n=120), Top Right (n=130), Down Left (n=94), Down Right (n=66), or center of the goal (n=76), and between passes directed at the side (n=105) or in depth (n=72);

k) Result, expressing the final result of the Free Kick, possibly being a goal (n=93), a save on shot (meaning a save from a direct shot on goal or from a shot coming from result of a cross or pass, n=297), a save on cross (meaning the goalkeeper caught or punched the ball in a cross, n=362), a block (the opposition blocked a shot, cross, or pass, potentially getting possession of the ball, n=1438), a miss on shot (n=491), a miss on a cross (n=201), and finally a foul (attacking or defensive, n=116).

	A	B	C	D	E	F	G	H	I	J	K
1	Freekick number	Season	Time	Attacking Club	Defending Club	Field Zone	Shooting Foot	People on the Wall	Free Kick Type: Shot, Cross, Pass or Touch	Direction of cross (1st post; center ; 2nd post; front) or Direction of Shot (Top Left; Top Right; Down Left; Down Right; Center) or Pass (side or depth)	Result (Goal, Save on shot, Save on cross, Block, Miss on shot, Miss on cross or foul)
2	1	19/20	60	Leixoes	Farense	RN	Left	1	cross	1st	block
3	2	19/20	65	Leixoes	Farense	LN	Right	1	cross	2nd	miss on cross
4	3	19/20	70	Leixoes	Farense	CLF	Right	2	cross	1st	miss on cross
5	4	19/20	72	Farense	Leixoes	LF	Right	1	cross	2nd	Save on cross
6	5	19/20	74	Farense	Leixoes	CLF	-	-	pass	depth	miss on cross
7	6	19/20	76	Farense	Leixoes	RF	Left	1	cross	center	Save on cross
8	7	19/20	81	Farense	Leixoes	LN	Right	1	cross	2nd	block
9	8	19/20	22	Varzim	Chaves	RF	Left	1	cross	2nd	Save on cross
10	9	19/20	38	Chaves	Varzim	CLN	Right	6	shot	Down Right	block
11	10	19/20	64	Chaves	Varzim	CRF	Right	1	cross	2nd	save on cross
12	11	19/20	67	Chaves	Varzim	RN	Right	1	cross	center	save on cross
13	12	19/20	76	Varzim	Chaves	RF	Left	1	cross	front	block
14	13	19/20	11	S.Covilha	Cova	LF	Left	2	cross	1st	miss on cross
15	14	19/20	17	S.Covilha	Cova	RF	Left	2	cross	center	Save on cross
16	15	19/20	34	Cova	S.Covilha	CLF	Right	1	pass	side	Foul
17	16	19/20	37	Cova	S.Covilha	RN	Left	2	cross	center	Save on cross
18	17	19/20	52	Cova	S.Covilha	RF	Left	1	cross	center	Save on cross
19	18	19/20	86	S.Covilha	Cova	CLF	Right	1	cross	2nd	Save on cross
20	19	19/20	87	Cova	S.Covilha	LF	Right	1	cross	1st	block
21	20	19/20	93	Cova	S.Covilha	RN	Right	1	cross	center	miss on shot

Figure 3.2: Free Kick data parameters. Example from our data base.

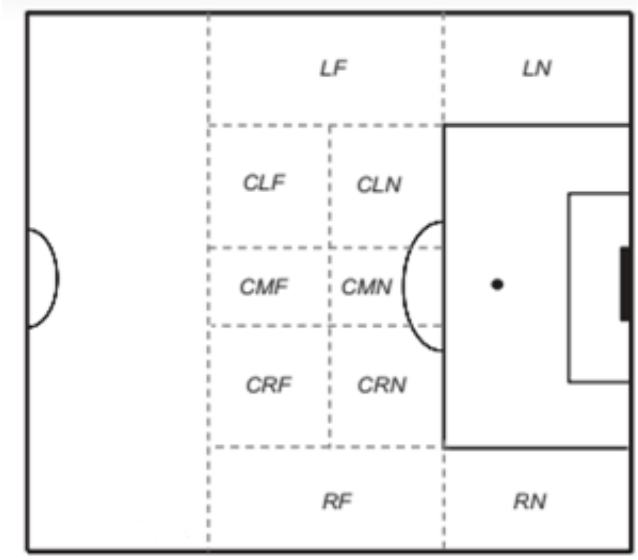

Figure 3.3: Different pitch locations used for data collection. LF – Left Far zone, LN – Left Near zone, RF – Right Far zone, RN – Right Near zone, CLF – Center Left Far zone, CLN – Center Left Near zone, CMF – Center Middle Far zone, CMN – Center Middle Near zone, CRF – Center Right Far zone, and CRN – Center Right Near zone (Adapted from [41])

3.2. Biomechanical Data Collection

As previously stated, the second phase of this project consisted of the capture of biomechanical parameters of Free Kick taking by young under-23 and second division players. Collection was performed in two practice pitches of the team, after the players' morning training session in the first half of the 2021/22 season, with the overview of the department of analysis and observation of the club, as well as with the permission of the Head Coaches of each team. The biomechanical parameters were of two types: kinematic parameters, such as speed or angles; and EMG data. Based on the first phase of this project, we selected the CLN and CRN zones, as the most interesting to analyze in this phase, as well as the CLF and CRF to provide information about the differences caused by distance. Players performed a minimum of four kicks per zone (more kicks could be performed if the player or the coaches wished it or found it necessary, and when two players performed kicks in the same zone each performed two at a time) in different orders depending on the day, as to not allow for one zone to always be the last, when the players were most tired, or first, where the opposite happened, and to prevent the effects of motor learning. All kicks were performed against an artificial four player barrier at a regular game distance, as per the choice of the coaches, where each artificial player had dimensions of 1.82x0.6m with a goalkeeper on the goal. The exact starting position of the goalkeeper was not defined in this investigation, and the ball used was of the same model in all of the trials.

3.2.1. Camera Setting

Different players approach the ball in different ways, some almost at a 0° angle, some at a 90° angle. Given that, we only had one camera to film the players' movement and the trajectory of the ball, the choice was made to film the movement at a 90° angle, ensuring we had good data from the players' movement at most times. Ball speed, which is the only parameter that was taken from the ball trajectory, unfortunately had to

be sacrificed most of the time for the movement of the player. The recording was performed with a GoPro Hero4 Silver camera, at 120 frames per second, with a narrow camera lens setting.

3.2.2. EMG Setting

In order to record EMG data from the subjects, first we had to assemble the BITalino setup to our convenience. Only the first three channels (of eight) of the BITalino were used. One wire cable was inserted in each channel. To the first channel cable, a three-lead electrode cable was added; on to the remaining channels, a two-lead electrode cable was added. Then, the BITalino was placed on a waist pack worn by the player. Electrodes were then coupled to the electrode cables. Two of the channel one electrodes were placed on the medial gastrocnemius muscle in a vertical orientation on top of the belly of the muscle. The third electrode was place on the bony zone of the ankle, serving as a ground for the system. Channel two electrodes were placed on the vastus lateralis muscle, also in a vertical orientation. The same was done with the channel three electrodes, place on the vastus medialis muscle. The electrode placements are shown in figure 3.4. To not severely restrain players' movements, the excess of the cords was rolled into the waist pack. In order to collect the data, the BITalino was connected wirelessly to our computer with the use of Bluetooth. Two Free Kicks were collected at a time in the OpenSignals software (1000 Hz sampling rate) to help prevent loss of signal (the longer the connection, the higher the probability of Bluetooth connection fails). To synchronize the EMG data with the video analysis we manually created "events" in the software upon the moment the foot of the player touched the ball, this way we were also able to have a better understanding of the EMG activation at the time of the kick.

Figure 3.4: Channel two electrodes on the vastus lateralis and channel three electrodes on the vastus medialis (Left), and channel one electrodes on the medial gastrocnemius (Right).

3.2.3. Player Subjects

Given that it is not relevant to this project, and at request of the team's staff, all of the involved players' identities are confidential, being referred to as player A up to player H. However, there is some player information of interest that must be presented. Eight players (18.6 ± 1.2 years) in total were involved in this study: five (17.8 ± 0.7 years) from the under-23 team and three (20.0 ± 0.0) from the B team, as we can see in table 3.1.

Table 3.1: Information of on players involved in the study, regarding the age of the players by each age group and the number of players in each group.

	Age	Number
All Players	18.6 ± 1.2	8
Under-23	17.8 ± 0.7	5
B Team	20.0 ± 0.0	3

All the players were right foot dominant, as to not implement another variable upon the study. The players had none, or minimal, body hair on the electrode application zones, as it helped in electrode to skin contact. All players were instructed to perform their kicks as they would in a normal scenario. Finally, a measurement of length between the head of the fibula and the lateral malleolus of the dominant leg was taken. This measurement allows us to define an established length on the video analysis, so that all the data of different players is correctly measured, despite different placements of the camera. To simplify, if we know the length between the knee and the ankle, all other measurements can derive from this one.

3.3. Biomechanical Data Analysis

To analyze the video footage captured at the training camp, we utilized the Kinovea software, a free to use biomechanical analysis program. We used this software to acquire the following biomechanical parameters:

- Last Stride Length;
- Support Leg Angle;
- Ball Speed;
- Maximum Velocity (Foot, Knee, and Hip);
- Distance Covered (Foot, Knee, and Hip);
- Velocity (Foot, Knee, and Hip).

After uploading our video file into the software, the first step, as previously stated, was to define our knee to ankle measurement, which will serve as the length value for the specific Free Kick. After measured, it can be placed at the corner of the video footage as to not create confusion with the other measurements, as seen on figure 3.5 (this figure will serve as an example for all parameters discussed in this subchapter). Afterwards, the first parameter assessed is the last stride length, which corresponds to the length between the spot where the right foot of the player leaves the ground in its final step towards the ball and the spot where the support foot hits the ground next to the ball, seen in the lower left zone of the image. Following

that, we measured the angle of the support leg upon impact of the dominant foot with the ball. The angle corresponds to the angle that the segments that go from hip to knee and from knee to ankle form. After being measured it can also be placed in a corner of the video, so to not disturb further assessments, as we see in the top right corner of the image. Next, we utilized the first four frames after foot-to-ball impact to gauge the length that the ball has traveled, as seen on the right side of the image. Knowing the conversion of frames to seconds, we then calculate the speed that the ball possesses as it leaves the players foot (we can talk of speed given that we can define the ball's movement as a straight line, resulting in distance and displacement being the same). Finally, we return to the frame where the dominant foot of the player leaves the ground and define a marker in the ankle, knee, and hip of the player. We are able to then track the movement of each marker from that frame on. For our study, we tracked the movement from that frame until the frame where the dominant foot impacts the ball, providing a path of the joints in the act of kicking. It is important to note that the tracking is not completely effective, resulting in a necessity to manually, frame by frame, adjustment of the positioning of the marker. When the path is complete it can be configured to show information regarding the total distance covered or the maximum velocity at each point. Firstly, we configured it to present us with the total distance covered, providing us with one of the parameters in study. Afterwards, we configured it to show the maximum velocity at each point. We then checked the movement frame by frame to discover the maximum value for each joint. In the example image, the frame where the maximum ankle velocity is present is shown. The last parameter is measured by dividing the distance covered by the joint, by the measure of time calculated from the number of frames the movement had, resulting in the velocity of movement of the joint. After all of this is done, we move to the next Free Kick and repeat the process.

Figure 3.5 - Example of the biomechanical parameters analyzed for each Free Kick performed.

After all this process was complete, all the data was analyzed statistically in order to compare our parameters between teams, nearest and farthest zones, and left and right zones. A study between parameters was also performed to check for possible impacts that one factor could have over another.

3.4. EMG Data Analysis

To analyze our EMG data, we returned to the OpenSignals software we use to record it. Due to time restraints upon recording, only players B and F (of the Under-23 team) and C and D (of the B team), performed the Free Kicks while wearing our EMG recording setup. Individual files, generally containing EMG activity of the performance of two Free Kicks, were analyzed, starting by player B, all the way to player F. After a specific file was selected, several BITalino channels are shown, out of which only the first three are of interest. Two evaluations were done. Firstly, in the Event tab on the top right of figure 3.6, we selected to show on each of our channels the exact moment at which we created an event (at the time of recording), which corresponded to the moment of foot to ball impact. These events are represented by the vertical grey lines on our graphs. This information we'll be used to ascertain the activation time of each of the muscle groups in our study. Afterwards, we analyze the RMS (root mean squared) of the average power of the EMG signal for each Free Kick muscle activation, as well as the duration of the activation for each muscle. To do this, we went to the EMG tab on the top right corner of the window. This tab allowed us, firstly, to define cutoff values to filter the signal. Based on the literature previously stated [81] [82] [83] [84], we chose to implement a bandpass filter with cutoff values of 20 Hz and 400 Hz. After these values are defined, with the help of the software, the signal is divided in specific windows where the signals parameters follow the settings. These windows can then be analyzed in regard to their RMS of the average power and to their duration. These specific intervals can be seen in figure 3.7. Two of these intervals can be analyzed at a time: with blue shading the first selected interval and a second with green shading.

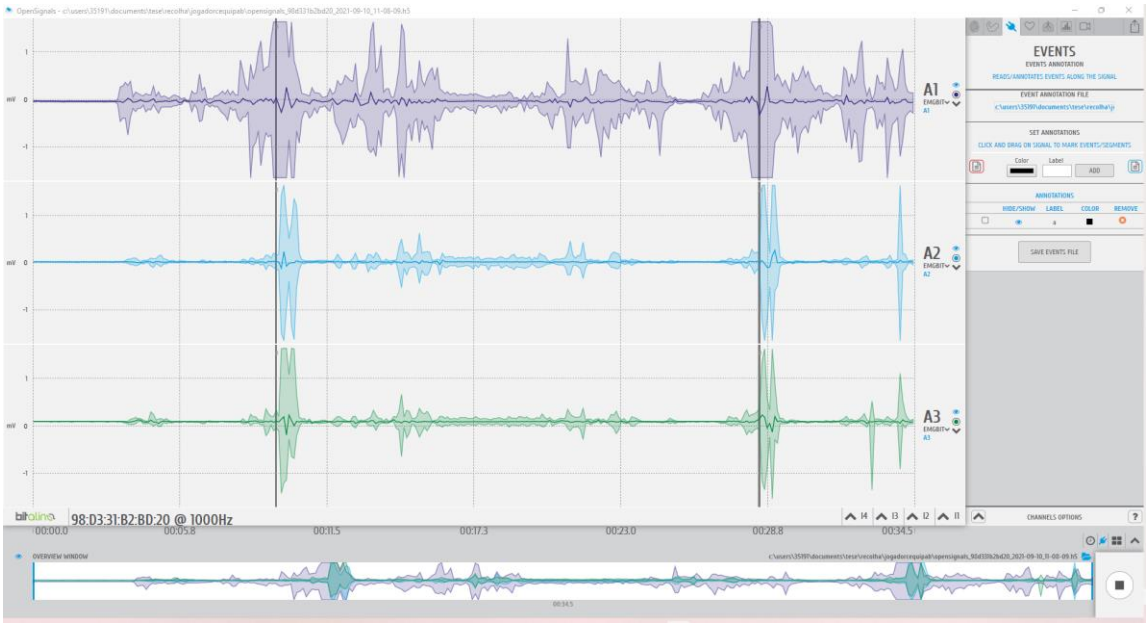

Figure 3.6: Event annotation on an EMG recording, visualized with the OpenSignals software, of three muscles (gastrocnemius medialis-A1, vastus lateralis-A2 and vastus medialis-A3) while performing two Free Kicks. Events, correspond to the foot to ball impact, and are shown as vertical grey lines.

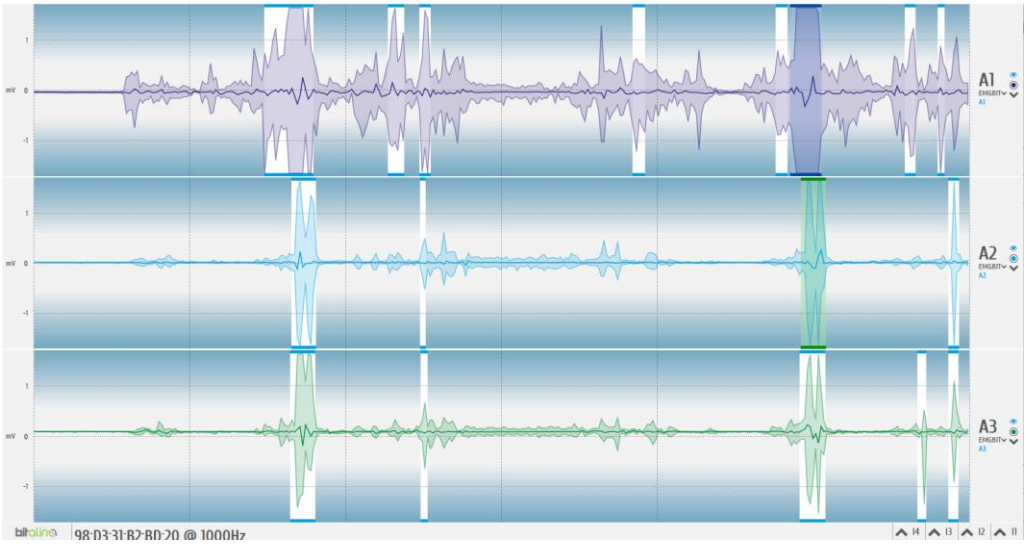

Figure 3.7: EMG readings in the OpenSignals software. Specific time windows where the EMG signal corresponds to the set parameters, allowing for possible analysis.

With the use of the EMG analysis tab, we can then check for the parameters of these windows, as seen on figure 3.8. Each window can be analyzed separately or the difference between each muscle can be analyzed. In this study, individual windows were analyzed. As stated, only the RMS and duration were collected from this information. However, the latency parameter represents the time at which the specific activation occurred, being helpful to confirm the findings of the event analysis previously done.

In a similar manner to the kinematic analysis, after this process was completed for all the files, a statistical study of the data was performed to compared between teams, nearest and farthest zones, and left and right zone. As before, a look between parameters was also performed to determine if any impact between them existed.

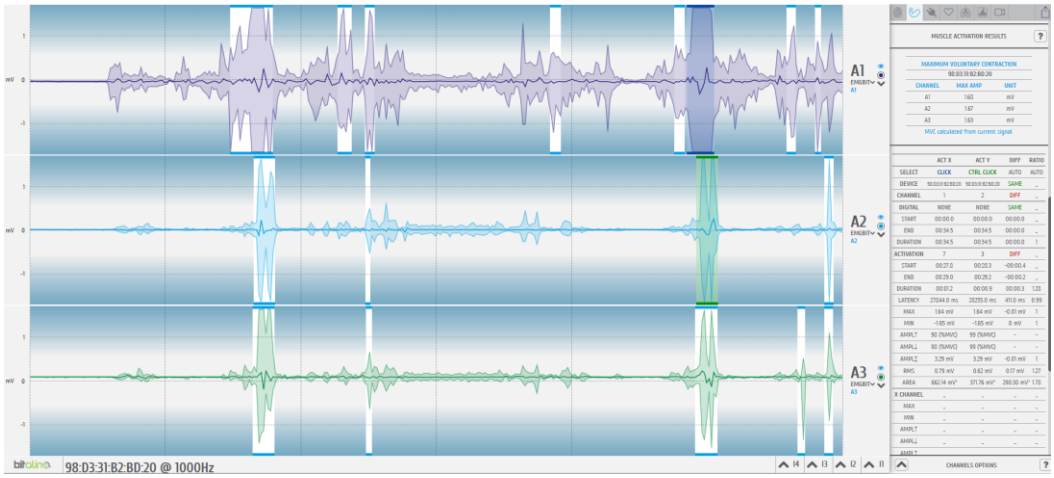

Figure 3.8: EMG readings in the OpenSignals software. Specific time windows analysis on the right side of the photo.

4. Results and Discussion

This chapter presents the dissertation's results and discusses their findings. Firstly, we present some findings of our general Free Kick data collection. Afterwards, a more extensive look on the biomechanical findings is presented, focused on kinematic parameters and EMG data.

4.1. General Free Kick Data Analysis Results

One of the goals of this dissertation was to have a better understanding of the importance and efficiency of Free Kick plays in football, specifically, on the league where the players investigated in this dissertation play. Therefore, and as stated before, a collection of data from 3000 Free kicks was performed (the information discussed in this chapter will be connected to the map of the pitch shown in figure 3.3 in the previous section).

From these results, our first findings show that it is most common for a Free Kick to be performed as a cross, as 2187 of 3000 Free Kicks are performed this way (72.90%), while direct shots were only performed 622 times (20.73%), as seen in figure 4.1. At first glance, it may appear that crosses are the better type of Free Kick. However, it is important to understand that different types of Free Kicks have different advantages depending on the zones where they are being performed from and, therefore, different threat levels. So, while it is a fact that crosses are most common, this is explained and reflected by the number of Free Kicks in each set of zones. As seen in figure 4.2, 1285 Free Kicks were performed from the farthest and lateral zones possible, seeing as it is more common for defenders to commit fouls in these zones, where the most reasonable course of action is to perform a cross that usually does not pose great threat for the defender's side.

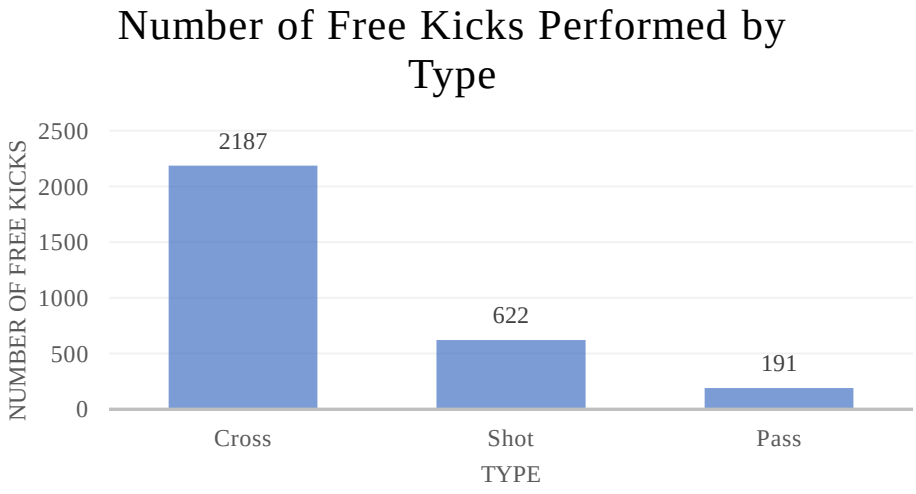

Figure 4.1: Number of Free Kicks performed by type: Cross (n=2187), shot (n=622), or pass (n=191).

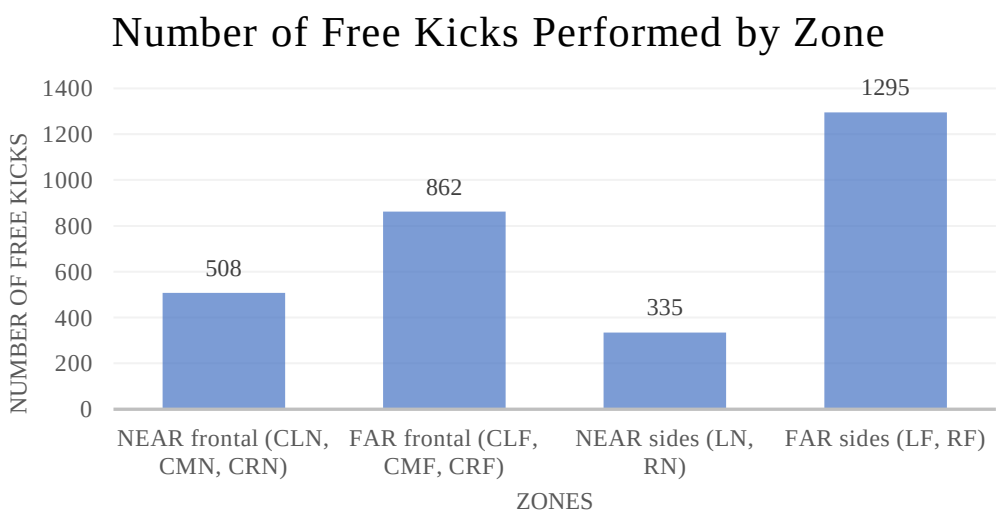

Figure 4.2: Number of Free kicks Performed by Zones: NEAR frontal (n=508), FAR frontal (n=862), NEAR sides (n=335), and FAR sides (n=1295).

It is easy to understand, that the nearest zones have the smaller number of Free kicks, because it is a more dangerous area and defenders are aware of it, avoiding committing fouls unless necessary. It is, therefore, also easy to understand why the nearest zones showed a higher percentage of goals, as seen in figure 4.3. With a percentage of 4.50% in the nearest frontal zones (CLN, CMN, and CRN) and of 3.90% in the nearest side zones (LN and RN), we can expect a little more than four goals per 100 shots, with a percentage of around three goals per 100 shots when discussing all zones. Although it may appear to be a small amount, four goals per 100 Free Kicks is a very promising number, that increases as the distance decreases, providing a steady number of goals per season for each club.

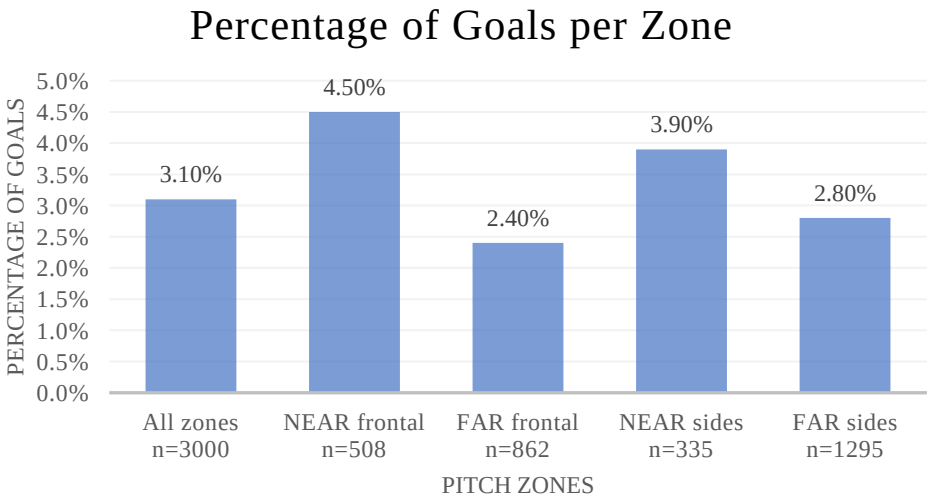

Figure 4.3: Percentage of Goals per zones on the pitch: all zones (3.10%), NEAR frontal (4.50%), FAR frontal (2.40%), NEAR sides (3.90%), and FAR sides (2.80%).

Besides, providing important information regarding the efficiency of Free Kicks, this data was also of relevance in order to determine which zones were of most importance to study the biomechanical parameters of Free Kick taking. Seeing as our biomechanical analysis revolves around Free Kicks performed as direct shots to goal, a look into the data of shots was performed. By focusing solely on the 622 shots performed in our data pool, we observed that the percentage of goal increased from the previous 3.10% to 4.50% across all of the analyzed zones (figure 4.4). Percentage of goals in the nearest frontal zones remained very similar with 4.40% (only a 0.1% difference), while all other zones increased their goal percentage. These results, however, appear to be, at first glance, counter intuitive, with the side zones showing a 6.25% (near zones) and 13.63% (far zones) chance of goal. These results can be explained by the small number of attempts, 23 from farthest zones and 32 from the nearest. From the side zones, these shots resulting in goal are probably due to a surprise factor and are, therefore, not the most important of Free Kicks to study.

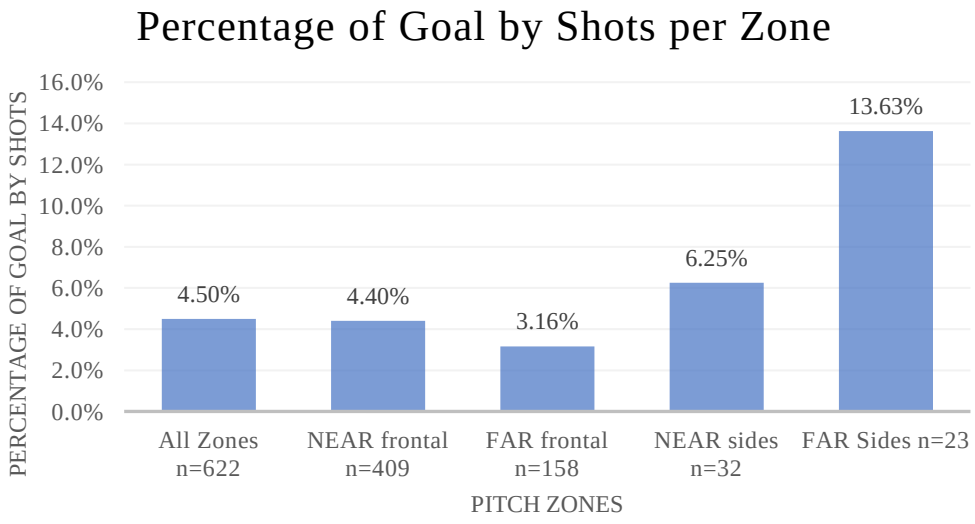

Figure 4.4: Percentage of goal by shots per zones: all zones (4.50%), NEAR frontal (4.40%), FAR frontal (3.16%), NEAR sides (6.25%), and FAR sides (13.63%).

The nearest frontal zones presented themselves as the most important for our biomechanical study due to their number (n=409), as well as their efficiency. However, the farthest frontal zones were also of interest to serve as a comparison setting for the data from the nearest zones, due to their more similar performance and number (n=158), while also representing a more interesting setting by themselves than the side zones.

Finally, regarding the pitch zones, we analyzed the specifics of the nearest frontal zones in order to understand the best way to prepare our biomechanical analysis. From our data we found that the CMN zone is the most efficient out of the three, showing a chance of goal from shots of 7.20% from 99 shots (figure 4.5). However, it appeared to us that the most interesting study would be of the left and right zone. It could appear to be counterproductive, but each of these zones is more common of a location for a Free kick to happen in game (n=160 in CLN zone and n=152 in CRN zone) and the fact that they represent different ways of performing the Free Kick due to their location, presents more interesting study comparisons than the middle location.

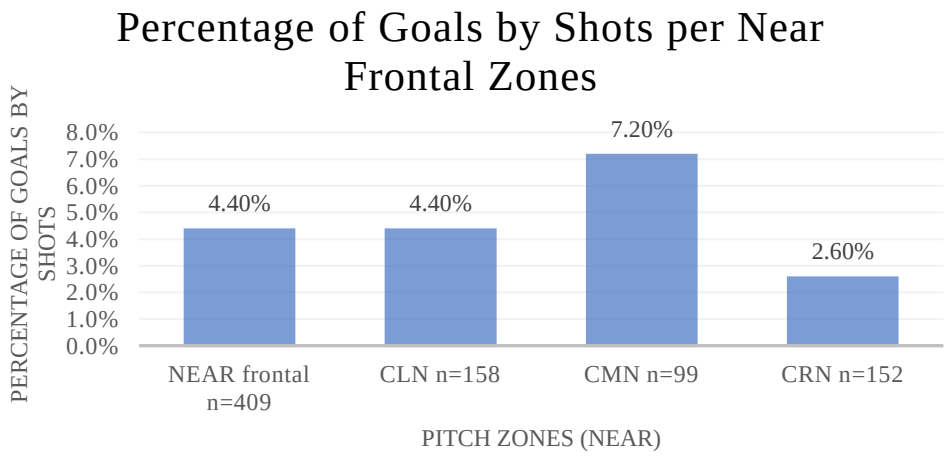

Figure 4.5: Percentage of goal by shots per near frontal zones: all zones (4.40%), CLN (4.40%), CMN (7.20%), and CRN (2.60%).

To conclude this section of results, we had final look towards Free Kicks performed as shots from the near frontal zones, with a focus on the direction of the shots. As we can observe from figure 4.6, most Free Kick shots are performed towards the top corners of the goal. However, more goals are scored when the shot is directed to the lower corners. Because of the player wall upon the performance of Free Kicks, lower corner directions are less common, possibly resulting in a higher efficiency due to its surprising factor and the lack of vision by the goalkeeper. It is understandable that top corner Free Kick directions are more common, also because those are the directions that are practiced in training.

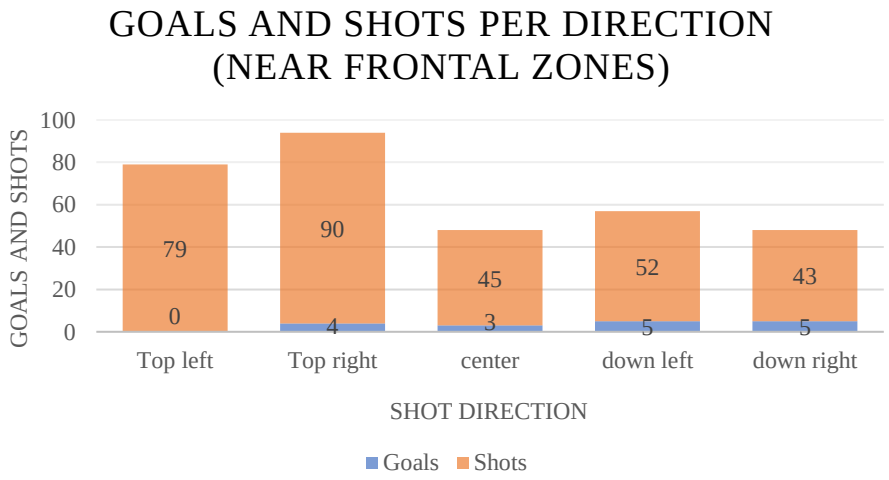

Figure 4.6: Number of goals (g) and shots (s) per direction: top left (g=0, s=79), top right (g=4, s=90), center(g=3, s=45), down left (g=5, s=52), and down right (g=5, s=43).

With the information collected in this section, the biomechanical data collection protocol was drawn. Data collection would be performed in the CLN, CRN, CLF and CRF zones, with a direction towards the top corners since the use of an artificial player wall to simulate game performance was applied.

4.2. Biomechanical Free Kick Data Analysis Results

The main goal of this master's dissertation was to research, identify, and compare the overlying technical and biomechanical factors involved in the performance of football Free Kicks by different aged players, players from different football competitive divisions, and from different pitch locations, either in distance or laterality. With the use of the Kinovea software and the OpenSignals software, we analyzed the data on both a kinematic view and an electromyographic view, respectively. The kinematic analysis allowed us to paint a superficial biomechanical picture of the movement of the Free Kick, while the EMG analysis complements it by giving an underlying view of the movement.

4.2.1. Kinematic Free Kick Data Analysis

From the video footage analyzed in the Kinovea software we identified and analyzed twelve different parameters, already discussed in section 3.3. We analyzed a total of 123 Free Kicks. However, not all of the analyzed Free Kicks were able to provide good enough conditions to all of the separate parameters. With every subject, our software expertise increased, allowing for a better planning, and analysis method with each new player. Even though this is a very good development, resulting in the second half of subjects analyzed parameters being of very good quality, our first subjects represent the opposite, with player A for example, only showing as analyzable parameters the angle of support leg on ball impact and ball speed. Another important setting information to consider is that the player does not perform the Free Kick with a 0° angle of movement towards the ball. Therefore, in no subject's analysis do we have good information of ball speed and movement parameters concurrently, seeing as we only had one camera available. As the project developed, we decided to focus on the movement parameters rather than ball speed, seeing as they provide more information about the performance of the Free Kick. Therefore, the ball speed analysis was sidelined.

After all the Free Kicks were analyzed and their parameter values annotated, they were coupled in groups, in order to perform the necessary comparisons to fulfill our main goal. They were divided between Free Kicks performed by the under 23 team or the B team, between the nearest pitch zones or the farthest pitch zones, and between the zones on the left side or those on the right side. P-values showed in the following sections were calculated through the non-parametric Mann-Whitney test, since we tackle two independent samples of Free Kicks.

4.2.1.1. Team-Based Kinematic Analysis

Firstly, we compared the under 23 team and the B team in support leg angle and in the distances traveled during the movement (Table 4.1). The under 23 team showed an average angle of the support leg 4.4° smaller than that of the B team. However, when we look at the distances, the under 23 team showed higher means all around. Not only was the mean distance traveled by all the joints higher (foot: 22.3 cm, knee: 15.2 cm, and hip: 10.7 cm), but the last stride length, representing the distance traveled in the final step in the approach to the ball, also showed a higher mean distance of 132.4 cm comparatively with the 127.9 cm of the B team.

Table 4.1: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks by under 23 and B team players.

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Under 23	134.3±6.5° (72)	132.4±16.0cm (53)	205.6±25.3cm (47)	118.0±17.9cm (50)	76.8±10.8cm (50)
B Team	138.7±6.4° (51)	127.9±17.4cm (32)	183.3±32.9cm (31)	102.8±13.5cm (32)	66.4±14.0cm (31)
p-value	0.0003*	0.1719	0.0072*	<0.0001*	0.0009*

*Significance at level 0.05. Sample size between brackets.

The higher mean distances of the under 23 team could, possibly, be explained by a lower muscle density when compared to the B team, resulting in a need to give their movement more momentum to create similar velocity values than those of older players. As for the angle, it appears that there is a tendency in our sample to increase that angle with age. In the literature, there seems to be a consensus that the angle that the support leg has upon ball impact serves to better absorb the forces present in the movement [65]. So, from our results we could possibly discern that this angle difference could be a result of the experience that the older players have to perform the kick with an angle that more efficiently absorbs the force of the movement.

Afterwards, the speed of the movement and the maximum velocity observed were analyzed (Table 4.2). In terms of speed throughout the movement, the under 23 team showed higher values than those of the B team. These differences were slight, but they were significantly different according to our statistical analysis. These could be seen as an experience difference. The lower values from the B team could possibly be a result of the more practice these players have in performing the Free Kick, not showing a need to push their speed to the maximum in order to cause danger to the keeper, while the younger players, as stated before, may feel a need to push harder to create more danger, possibly causing a higher lack of accuracy. However, as mentioned, these differences are very small when compared to the differences in distance. Regarding the maximum recorded velocity during the movement there is no clear general differences. While the B team shows a very slightly higher average in foot and hip max velocity, the under 23 team show a higher knee velocity average. Seeing as it would be strange to assume that the young players are able to possess a higher velocity in their knee joint than in the other two joints when compared with the older players, we are forced to assume that the small human errors during measurements may explain these very slight differences. However, it is once again of note that the younger players did possess a similar maximum velocity to that of older players, contrary to what could be expected from the literature [51] [65].

Table 4.2: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks by under 23 and B team players.

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Under 23	9.1±1.1m/s (48)	5.3±0.8m/s (50)	3.4±0.5m/s (50)	21.9±3.1m/s (51)	9.5±1.9m/s (40)	4.4±0.6m/s (49)
B Team	8.5±0.8m/s (29)	4.9±0.5m/s (32)	3.1±0.5m/s (31)	22.3±3.3m/s (41)	9.2±1.4m/s (41)	4.6±0.6m/s (40)
p-value	0.0081*	0.0062*	0.0016*	0.4578	0.0001*	0.2953

*Significance at level 0.05. Sample size between brackets.

4.2.1.2. Distance-Based Kinematic Analysis

In order to continue our main goal analysis, we followed our study with a comparison of our parameters between the nearest zones (CLN, CRN) and the farthest zones (CLF, CRF). As in the team based analysis, firstly, we compared the values of the support leg angles and distances traveled (Table 4.3). We observed that Free Kicks performed from longer distances showed greater support leg angle (138.8°) than those performed closer (133.9°). This result also corresponds to the literatures' findings. It is assumed that, since the Free Kick is performed from a farthest distance, the player must exert more force than usual, resulting in a need for the support leg to absorb more force, shifting to a more open angle when performing Free Kicks from this distance. The choice for a more open angle may help on the force absorption, given that the support leg has a higher range of motion to absorb the power as the movement follows through after the ball impact. The distance to the goal did not seem to have any impact on the length of the last stride, meaning that the way the player approaches the ball does not seem to be impacted. Regarding the joint distances, we did not see significant differences in the knee and hip movements as they are very small, but also in that the knee traveled longer distances in the nearest zones, while the hip showed the opposite. Where we noticed a big discrepancy is in the distance traveled by the foot. Again, against what could be expected, in our study the foot traveled 10.3 cm more on average in the nearest zones of the pitch.

Table 4.3: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Near and Far zones).

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Nearest Zones	133.9±6.6° (67)	130.7±14.5cm (39)	198.7±32.7cm (39)	113.8±17.4cm (39)	71.2±11.7cm (39)
Farthest Zones	138.8±6.2° (58)	130.6±18.8cm (44)	188.4±33.9cm (43)	110.5±18.4cm (43)	74.4±14.1cm (42)
p-value	0.0001*	0.8875	0.1827	0.5217	0.2627

*Significance at level 0.05. Sample size between brackets.

In terms of joint speed throughout the movement we again see very similar values in both zones (Table 4.4), with a slightly greater foot speed in the nearest zones and greater hip speed in the farthest zones. These values relate to the joint distance values that showed the same type of differences, resulting again in an interesting contrast to what could be expected. The maximum joint velocity averages also go in line with these findings. However, these parameters show a greater difference in the knee velocities than in the foot velocities. These slight differences between joint distances, speeds, and maximum velocities could be explained by a small sample size or by the human margin of error in the measurements and video analysis. Nonetheless, it appears to be clear that no exceedingly significant large differences can be seen between distances in these parameters.

Table 4.4: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Near and Far zones).

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Nearest Zones	9.2±0.7m/s (35)	5.2±0.7m/s (39)	3.2±0.4m/s (39)	22.2±3.0m/s (46)	9.9±1.1m/s (43)	4.5±0.4m/s (45)
Farthest Zones	8.6±1.3m/s (43)	5.1±0.8m/s (43)	3.4±0.6m/s (42)	22.0±3.5m/s (46)	9.1±1.9m/s (45)	4.6±0.7m/s (43)
p-value	0.0335*	0.6253	0.1225	0.9595	0.0973	0.2001

*Significance at level 0.05. Sample size between brackets

In order to study more deeply these parameters, we separated the analysis between the two teams to verify the general analysis that was done, these tables can be found on appendix A. With the analysis of the under 23 team we also observed an increase of the angle of the support leg in the farthest zones. Most other parameters did not appear to vary much, however there was a slight increase in foot distance travelled and max velocity in the nearest zones, contrary to expected. In terms of the B team, we again observed an increase in the angle of the support leg. This time we observed slightly greater, but not significant, values of the parameters in the farthest zones, especially in regard to the distances travelled by the joints.

4.2.1.3. Laterality-Based Kinematic Analysis

We concluded our main parameter analysis with a comparison study between the zones of the pitch on the left side (CLN, CLF) and the ones on the right side (CRN, CRF). In the same way as before, we started by analyzing the support leg angle and the traveled distances (Table 4.5). Again, the support leg angle averages show a very significant difference between zones, with a 4.0° degree greater angle average from the right zone kicks. Since our study focuses on right footed players, one explanation for these values could be that because the player must perform a slightly larger rotation of their body to direct their kicks towards goal, the support leg reacts accordingly, increasing its angle to better accommodate the increase force caused by the extra rotation. The results of the last stride length averages could also be explained by this extra rotation. The extra 9.5 cm of length could help in the creation of more hip rotation that would be necessary for

improving the performance of the Free Kicks from this side of the pitch. The differences in average distances traveled by the joints also corroborate this assumption. Differences of 9.2 cm, 6.2 cm, and 2.0 cm in foot, knee, and hip distances, respectively, with the greater distances being traveled in the right zone, show that there is a need for that extra movement in those zones, probably due to the mentioned need for extra rotation.

Table 4.5: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Left and Right zones).

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Left Zones	134.2±6.0° (64)	126.1±14.2cm (43)	188.8±30.9cm (42)	109.1±15.9cm (43)	71.9±12.7cm (42)
Right Zones	138.2±7.1° (61)	135.6±18.1cm (40)	198.0±35.6cm (40)	115.3±19.5cm (39)	73.9±13.4cm (39)
p-value	0.0022*	0.0113*	0.1613	0.0928	0.3975

*Significance at level 0.05. Sample size between brackets

In terms of speed and maximum velocities (Table 4.6), values are very similar between zones, showing no significant differences throughout. In contrast with the distance based analysis, these values go according to what could be expected. While there may be a need for rotation and longer joint distances in the movement to compensate the laterality, there is no real need for the Free Kicks to have more or less speed, given that they are performed from similar distances. However, we can observe very slight speed and maximum velocity variations in favor of right zone kicks that could be explained as a side product of the extra rotation.

Table 4.6: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Left and Right zones).

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Left	8.6±1.0m/s (42)	5.0±0.7m/s (43)	3.3±0.5m/s (42)	22.1±3.3m/s (43)	9.2±1.7m/s (43)	4.4±0.6m/s (42)
Right	9.0±1.3m/s (40)	5.2±0.8m/s (39)	3.3±0.5m/s (39)	22.1±3.1m/s (49)	9.4±1.6m/s (48)	4.6±0.6m/s (47)
p-value	0.1874	0.2847	0.3507	0.9594	0.7144	0.1242

*Significance at level 0.05. Sample size between brackets.

Again, in order to study more deeply these parameters, we separated the analysis between the two teams to verify the general analysis that was done, these tables can be found on appendix B. With the analysis of the under 23 team we also observed an increase of the angle of the support leg in the zones to the right. We also observe a significant increase in the last stride length in the zones to the right, and a slight increase in distances travelled by the joints in these zones as well. As in the more general analysis these greater distances did not result in increased velocities. In terms of the B team, we again observed an increase in the angle of the support leg. However, in the B team we only observed an increase in the last stride length and in the distance travelled by the foot. Again, these results did not result in increased velocities of the movement.

4.2.1.4. Speed and Maximum Velocity Influences

From our review of the literature in this field, it is wildly considered that ball speed is a main factor in the success of the Free Kick [34] [35]. The greater the speed the best the chance to score a goal. From the literature we also know that the foot speed directly correlates to the ball speed [53] [59]. Greater foot speed corresponds, in general, to greater ball speed. So, foot speed (or its velocity) is the parameter involved in the player's movement that most easily can relate to a greater chance of goal. Therefore, it is of interest to check some factors that may influence the speed of this joint.

Since in all our previous findings the support leg angle values provided very valuable and significant information, we started by analyzing if there would be any average speed differences between smaller or greater angles (Table 4.7). We observed very small differences in speed and maximum velocity, with greater foot speed values for greater angles, but greater maximum foot velocities for smaller angles.

Table 4.7: Foot speed and maximum foot velocity during the performance of Free Kicks with different support leg angles.

Angle	Foot Speed	Max Foot Velocity
< 138º	8.6±1.1m/s (41)	22.2±3.3m/s (44)
>= 138º	9.0±1.3m/s (41)	22.0±3.2m/s (48)
p-value	0.2119	0.9097

*Significance at level 0.05. Sample size between brackets.

Afterwards, we checked if the distances, both the last stride length and foot distance, had any influence on the speed. Firstly, we divided the Free Kicks between those with a last stride length of less than 130 cm and those with more or equal value (Table 4.8). In contrast with the angle influence, we observed that the length of the last stride appears to impact greatly the speed and maximum velocity of the foot. The differences observed are not small, being of 1.6 m/s in terms of the speed throughout the movement and of 2.9 m/s in terms of maximum speed. These differences, as discussed in section 4.2.1.1, are probably the result of a greater momentum generated by the longer lasting stride, along with other factors.

Table 4.8: Foot speed and maximum foot velocity during the performance of Free Kicks with different last stride lengths.

Last Stride Length	Foot Speed	Max Foot Velocity
< 130 cm	8.0±0.9m/s (41)	20.3±3.4m/s (41)
>= 130 cm	9.6±0.9m/s (41)	23.2±2.2m/s (42)
p-value	< 0.0001*	< 0.0001*

*Significance at level 0.05. Sample size between brackets.

Finally, we compared Free Kicks with foot distances of less or equal to 200 cm with those with longer foot distances (Table 4.9). In the same way that greater last stride lengths seemed to influence speed, greater foot distances appear to impact it the same way. We observed very similar differences as before, with an increase of 1.4 m/s in foot speed with greater foot distances, and of 4.3 m/s in terms of maximum foot velocity averages. These results come to better explain why in section 4.2.1.1 we observed a "need" of the younger players to perform longer movements in order to compete with the older players power, or why in the zones most to the right we also noted a slight increase in speed due to the extra movement probably caused by the greater rotation of the body.

Table 4.9: Foot speed and maximum foot velocity during the performance of Free Kicks with different foot distances.

Foot Distance	Foot Speed	Max Foot Velocity
<= 200 cm	8.1±1.0m/s (41)	19.6±3.0m/s (41)
> 200 cm	9.5±0.9m/s (41)	23.9±1.6m/s (41)
p-value	< 0.0001*	< 0.0001*

*Significance at level 0.05. Sample size between brackets.

4.2.2. EMG Data Analysis Results

To continue our investigation towards our main goal of researching, identifying, and comparing the overlying technical and biomechanical factors involved in the performance of Free Kicks by different aged players, from different pitch locations, either in distance or laterality, we moved to the EMG side of these results. With the use of the OpenSignals software, we identified and analyzed two parameters, while also collecting information about the time of muscle activation.

The amount of analyzable Free Kicks in this section is lower than we would have wanted due to several factors. Firstly, due to time constraints upon the time of recording, we could only record EMG data from four subjects (initially five, but player's A data was not viable). Secondly, due to errors in Bluetooth connection between the BITalino and the computer, some data was lost in each session. Due to the

"violence" of the kicking motion, our material (mainly the cables) got increasingly damaged, needing fixing throughout, resulting in increasingly different data. The "violence" of the kick also meant that, occasionally, our electrodes would separate from the individual, losing the data of that Free Kick. The final number of Free Kicks analyzed was of 37.

After all the Free Kick parameters were collected from the OpenSignals software, they were coupled in groups as in section 4.2.1. They were divided between Free Kicks performed by the under 23 team or the B team, between the nearest pitch zones or the farthest pitch zones, and between the zones on the left side or those on the right side. P-values were calculated using the non-parametric Mann-Whitney test, since we tackled two independent samples of Free Kicks.

4.2.2.1. Team-Based EMG Analysis

We started by comparing the RMS of the average power of the EMG and the duration of the contraction between the Under 23 team and the B team (Table 4.10). The Under 23 team showed lower muscle power in their medial gastrocnemius (0.68 mV to 0.78mV) and vastus lateralis (0.48 mV to 0.60 mV) but a greater power in their vastus medialis (0.64 mV to 0.52 mV) when compared to the B team. Seeing as the gastrocnemius is the main plantar flexor muscle, it could be assumed from these results that the B team possessed a greater control over their foot movement than the under 23 team, being able to exert greater forces during a longer period of time. On the other hand, the quadricep muscles show interesting results, with each one showing greater power for a different team. It is difficult to reach a conclusion regarding these values, but because the B team shows greater activation in the larger of the thigh muscles, we could assume that because of their age and experience they more easily activate the muscles that allow for a more powerful strike. Another explanation could be that, in our sample group, the younger players performed the Free Kicks with a different approach to the ball (more front facing) than the B team players (more laterally facing), resulting in a need for the different muscles to activate in different magnitudes. From these results we can also observe that the gastrocnemius is activated for a longer duration than the quadricep muscles.

Table 4.10: RMS of the average power of the EMG signal and duration of activation of the three analyzed muscles (Medial Gastrocnemius, Vastus Lateralis, and Vastus Medialis) during the performance of Free Kicks by under 23 and B team players.

	Medial Gastrocnemius		Vastus Lateralis		Vastus Medialis	
	RMS	Duration	RMS	Duration	RMS	Duration
Under 23 Team	0.68±0.07mV (16)	1.6±0.3s (16)	0.48±0.10mV (9)	1.1±0.1s (9)	0.64±0.16mV (16)	1.2±0.1s (16)
B Team	0.78±0.08mV (21)	1.9±0.5s (21)	0.60±0.14mV (22)	1.1±0.2s (22)	0.52±0.11mV (19)	1.2±0.3s (19)
p-value	0.0004*	0.1048	0.0235*	0.4212	0.0232*	0.6775

*Significance at level 0.05. Sample size between brackets.

4.2.2.2. Distance-Based EMG Analysis

To continue our analysis, we followed our investigation with a comparison between the nearest zones (CLN, CRN) and the farthest zones (CLF, CRF) (Table 4.11). In terms of the medial gastrocnemius, we observe very similar RMS results between the zones, showing that the role of the lower leg muscle does not suffer change with distance. The quadriceps, however, especially in the vastus medialis muscle show a larger difference in RMS, 0.51 mV for the nearest zone and 0.64 mV for the farthest zones. The most logical explanation for this difference is that with the increase in distance there is a need to increase the power output of the upper leg muscles, in order to extend the leg in a more powerful manner to transmit the most force to the ball upon impact. This increase attempts to compensate for the distance to still cause danger to the goalkeeper. Again, we observe that the duration of the activation of the gastrocnemius muscle is longer than that of the quadricep muscles.

Table 4.11: RMS of the average power of the EMG signal and duration of activation of the three analyzed muscles (Medial Gastrocnemius, Vastus Lateralis, and Vastus Medialis) during the performance of Free Kicks in different pitch zones (Near and Far zones).

	Medial Gastrocnemius		Vastus Lateralis		Vastus Medialis	
	RMS	Duration	RMS	Duration	RMS	Duration
Nearest Zones	0.75±0.10mV (17)	1.7±0.5s (17)	0.55±0.13mV (14)	1.1±0.2s (14)	0.51±0.12mV (18)	1.2±0.1s (18)
Farthest zones	0.72±0.09mV (20)	1.9±0.4s (20)	0.58±0.14mV (17)	1.1±0.2s (17)	0.64±0.15mV (17)	1.2±0.2s (17)
p-value	0.5412	0.0941	0.7657	0.5276	0.0115*	0.5005

*Significance at level 0.05. Sample size between brackets.

4.2.2.3. Laterality-Based EMG Analysis

To conclude our main parameter a comparison between the zones of the pitch on the left side (CLN, CLF) and the ones on the right side (CRN, CRF) was done (Table 4.12). Overall, we observe no significantly large differences between the two zones. The slightly greater RMS values in the zones to the right are not, in our view, large enough for us to assume that there exists any difference in muscle power when performing the Free Kicks in the left or right zones. Again, as in the other analysis, the gastrocnemius is activated for a longer period of time than the quadriceps muscles.

Table 4.12: RMS of the average power of the EMG signal and duration of activation of the three analyzed muscles (Medial Gastrocnemius, Vastus Lateralis, and Vastus Medialis) during the performance of Free Kicks in different pitch zones (Left and Right zones).

	Medial Gastrocnemius		Vastus Lateralis		Vastus Medialis	
	RMS	Duration	RMS	Duration	RMS	Duration
Left Zones	0.72±0.07mV (16)	1.9±0.5s (16)	0.52±0.14mV (14)	1.1±0.2s (14)	0.56±0.15mV (13)	1.2±0.2s (13)
Right zones	0.75±0.10mV (21)	1.7±0.4s (21)	0.60±0.13mV (17)	1.1±0.2s (17)	0.58±0.15mV (22)	1.2±0.2s (22)
p-value	0.1864	0.6541	0.0676	0.7754	0.8243	0.4010

*Significance at level 0.05. Sample size between brackets.

4.2.2.4. EMG Influence in Speed and Maximum Velocity

In the same way that we analyzed the influence of kinematic parameters in the speed and velocity values, in this subsection we analyze the impact of each muscle's power in those parameters (Tables 4.13, 4.14, 4.15). In contrast with the previous analysis, these results indicate no real influence between the muscle power and speed and velocity differences. However, this sample is considerably smaller, as stated in section 4.2.2. Therefore, the lack of impact could be explained by the lack of data. The vastus lateralis shows greater speed and velocity differences (greater speed and velocity values for greater muscle power), in accordance with what would be expected. However, as stated, no real conclusions can be taken from these data.

Table 4.13: Foot speed and maximum foot velocity during the performance of Free Kicks with different medial gastrocnemius RMS values.

Medial Gastrocnemius RMS	Foot Speed	Max Foot Velocity
<= 0.71 mV	9.1±1.5m/s (13)	21.3±2.3m/s (13)
> 0.71 mV	8.6±1.4m/s (14)	21.0±3.4m/s (16)
p-value	0.4373	0.8607

*Significance at level 0.05. Sample size between brackets.

Table 4.14: Foot speed and maximum foot velocity during the performance of Free Kicks with different vastus lateralis RMS values.

Vastus Lateralis RMS	Foot Speed	Max Foot Velocity
<= 0.50 mV	8.0±0.9m/s (11)	19.5±1.1m/s (11)
> 0.50 mV	8.8±1.5m/s (9)	21.3±3.7m/s (11)
p-value	0.1832	0.1779

*Significance at level 0.05. Sample size between brackets.

Table 4.15: Foot speed and maximum foot velocity during the performance of Free Kicks with different vastus medialis RMS values.

Vastus Medialis RMS	Foot Speed	Max Foot Velocity
<= 0.50 mV	9.4±1.3m/s (13)	21.1±2.7m/s (13)
> 0.50 mV	8.7±1.6m/s (11)	21.6±3.3m/s (13)
p-value	0.2023	0.5046

*Significance at level 0.05. Sample size between brackets.

It is of note, that in almost the entirety of our Free Kicks, the medial gastrocnemius always activates before the quadriceps muscle. This is explained by this muscle's role. As one of the main plantar flexors, as it activates the foot extends in preparation for the kick. The foot must be in position before the impact, explaining why the gastrocnemius muscle shows an earlier activation.

5. Conclusions and Future Work

Nowadays, for a sports team to improve, it cannot only depend on their players' skills. We have observed that when a sport or a team embraces the help of technology, performance analysis, and sports science, it consistently improves, surpassing their competitors. Therefore, in this dissertation, it was performed an in depth study on the underlying factors that differentiate between football Free Kicks performed by different aged players and in different pitch zones. With this investigation, we expected to be able to present a clear picture of the differences between settings and samples, that could help teams, coaches, and players, to better practice and prepare Free Kicks.

Firstly, it was performed an extensive Free Kick parameter analysis of the Portuguese second division on the course of three seasons, in order to define, in a more concrete way, the efficiency that we could expect from Free Kicks and their subsequent variables, and the most appropriate settings for our biomechanical investigation. We were able to assess that the Free Kicks taken closer to goal were more dangerous for the goalkeeper than those taken from farthest distances. However, in what regards laterality the same cannot be said. Free Kicks taken from the sides are, generally, as dangerous as the frontal ones, mainly because these Free Kicks are played as crosses towards the goalkeeper area.

Secondly, with the conclusions taken from the first part of this project being that we should analyze the CLN, CRN, CLF and CRF zones, we analyzed a total of 123 Free Kicks from a kinematic standpoint and 37 from an electromyographic standpoint.

From our kinematic analysis we observed, throughout our comparisons, that there were significant differences in the support leg angle, in both age and pitch location. We could assess that, as a mechanism of force absorption, the support leg possessed a greater angle when there was a greater need to absorb the impact from the kick. More distance means more power and, therefore, a greater need to absorb the impact. Free Kicks from the right require more rotation and, thus, require a greater angle. Finally, an increase of angle with age could be a sign of experience.

One of our most significant analyses showed that greater joint distances and last stride lengths have a clear impact on foot speed and, therefore, ball speed. Meaning that, to perform a Free Kick with greater speed a player should perform a wider and more complete movement. Interestingly, in our study we also observed that the under 23 team performed the Free Kicks with greater traveled joint distances than the older players. However, these greater joint travel distances observed in the younger players did not correspond to greater speed values. Because the younger players have less muscle mass, the increase in length of the movement allows for similar speed values, but not greater, as the older players more easily can input power on the movement.

In terms of distance, we could have expected wider movements from the farthest zones in order to perform the Free Kicks with greater speeds. However, we did not observe this. Most values, both in distance traveled values and in speed values, were quite similar between distances. The foot distances and speed values were even slightly greater in the closest zones, in contrast with what could be expected.

Regarding the laterality of the Free Kick, we observed a clear pattern of increased traveled distances in the zones to the right. These values did not correspond, however, to greater speed values. This can be explained by the rotation that is needed in these zones. Seeing as the zones to the right require greater rotation of the body, the increased distances serve to allow for this. However, the rotation does not mean more speed. This

means that, even though there is a general impact of joint distances in speed, when there is an increase in joint distances to create more rotation to compensate for laterality, this does not necessarily represent an increase in movement speed, as can be shown from the results.

Lastly, we analyzed the EMG data for the same settings. The average power of the medial gastrocnemius muscle was always greater than that of the quadriceps muscles, and its activation was always longer and started sooner than that of the other muscles, for each of the testing settings (under 23 vs B team, Near vs Far, Left vs Right). As it is the main plantar flexor muscle, this activation shows us that the preparation of the foot for the impact with the ball starts earlier than the extension of the leg, possibly to give the player more control of the placement of the foot when it impacts the ball. Between the younger and older players we observed a difference in quadricep muscle activation, with the younger players showing greater muscle power in the vastus medialis and lower muscle power in the vastus lateralis. The most probable explanation is that in our reduced sample, the younger players performed the kick with a different approach (front facing) to that of the older players (more lateral facing). In regard to distance, we observed, in accordance with what could be expected, that the Free Kicks performed from a farthest distance show greater average muscle power in the quadriceps muscles. This makes sense, given that we expect that Free Kicks performed from farthest distances need to be performed with more power in order to create danger to the goalkeeper. As for our laterality assessment, the slight differences in muscle power are not, in our view, large enough for us to assume that there exists any difference in muscle power when performing the Free Kicks from the left or right zones. Finally, we observed no impact between muscle power in any of the muscles and foot speed or maximum velocity values. This can be explained, mainly, by the small sample in our EMG analysis, due to all of the limitations that impacted the study.

Some limitations of the study are worth noting. Firstly, our data collection setting was perfected throughout the study, meaning that upon collection of the data of our last subjects the setting was optimal, but with our first subjects a lot of setting errors meant that some of our data was not usable, or not of the best quality. Secondly, our sample, although of a very generous size, was not large enough to consider a comparison between Free Kicks that resulted in goals and the rest of the Free Kicks. It is also noteworthy that the players' height, which was not assessed in this study, could be a parameter of influence in the performance of the Free Kicks. Finally, our EMG sample was shorter than expected, due to time constraints upon the time of recording, errors in Bluetooth connection between the BITalino and the computer, and due to the "violence" of the kicking motion, our material, mainly our cables, got increasingly damaged, needing fixing throughout, resulting in increasingly different data. The "violence" of the kick also meant that, occasionally, our electrodes would separate from the individual, losing the data of that Free Kick.

Overall, this study met the objectives set forth on its inception. It is demonstrated that several overlying technical and biomechanical factors of the performance of Free Kicks differ when comparing different aged players and teams, different distances towards goal, and a different pitch laterality, both in a kinematic view and in an electromyographic view. Pertinent information not previously investigated was observed and should be of greater interest to add to the literature on this field.

This study raises new research questions that could be investigated in future studies. In this dissertation the relationship between height and Free Kick performance was not investigated and should be a very interesting factor to analyze. The same could be said of the study of the middle pitch zones that were not investigated. Are their parameters going to differ from the other frontal pitch locations analyzed in this dissertation? Or are their differences not significant enough to make that assumption? Due to the lack of

data, a comparison between successful and unsuccessful Free Kicks could not be performed. A study that was able to focus on this could be of great interest not only for the literature in the field, but especially to the teams. A more in depth analysis of our EMG parameters would also be of interest, with a bigger sample than the one presented in this dissertation. It would also be of great interest to analyze the difference between agonist and antagonist muscles in this movement. Finally, the addition of a gender analysis could also be of interest, in order to study the differences in movement and in muscle activation in Free Kicks between male and female football.

5.1. Findings

Since this dissertation is very extensive, here in this final subchapter, we present the more exact and practical findings of this dissertation. The first three findings are of interest in a practical way, meaning that they are of use for the teams. The last three findings are of more general scientific interest.

Firstly, there is an increase in the angle of the support leg when there is a need to implement more strength to the players' shot, however an increased angle does not mean more velocity, only better impact absorption and injury prevention. Secondly, the longer the last stride length and the longer the movement of the joints the more velocity it appears to be implemented to the ball, therefore increasing Free Kick success. Thirdly, in terms of laterality we observed a clear pattern for longer distances travelled on the right side of the pitch, but these results did not correspond to greater velocities, why? Because they serve as a mechanism for the rotation of the body so that the ball can be directed towards goal, meaning that the extra effort it comes with does not increase Free kick success. This specific result shows us that it makes more sense to have right footed players shooting from the left side and left footed players shooting from the right side not only to have the ball running away from the goalkeeper during the shot but because the players own physiognomy allows for greater Free Kick success in this way.

In terms of our more scientific results, firstly, we did not observe longer movements or greater speeds in the farthest zones, contrary to what could be expected. In talks with the staff of the team that was analyzed, the only explanation for this would be that no specialist in far Free Kicks was analyzed in our study. Secondly, the gastrocnemius muscle had a longer, stronger and earlier activation than the quadriceps, which indicates that the preparation of the foot positioning on impact comes before the muscle activation of the thigh that provides power to the shot. Finally, in terms of distance and as expected, we observed greater muscle activation from the quadriceps in the farthest zones.

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Appendix

Appendix A

Table A.1: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Near and Far zones) by the Under 23 team.

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Nearest Zones	131.4°±5.8 (38)	132.4±15.8 cm (27)	208.1±32.9 cm (27)	120.0±16.9 cm (27)	76.4±10.0 cm (27)
Farthest Zones	137.5°±5.9 (34)	132.3±17.0 cm (24)	189.5±29.4 cm (24)	115.6±19.2 cm (23)	77.3±23 cm (23)
p-value	<0.0001*	0.6919	0.0145*	0.5527	0.6614

p-value calculated for a significance level of 0.05.

Table A.2: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Near and Far zones) by the Under 23 team.

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Near	9.0±1.2 m/s (27)	5.2±0.7 m/s (27)	3.3±0.4 m/s (27)	22.7±2.9 m/s (27)	9.9±1.5 m/s (27)	4.4±0.5 m/s (27)
Far	8.8±1.2 m/s (24)	5.4±0.9 m/s (23)	3.6±0.5 m/s (23)	21.0±3.2 m/s (24)	8.9±2.1 m/s (23)	4.5±0.6 m/s (22)
p-value	0.533	0.0837	0.0341*	0.0415*	0.1817	0.1463

p-value calculated for a significance level of 0.05.

Table A.3: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Near and Far zones) by the B team.

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Near	137.1°±6.3 (29)	126.7±10.5 cm (12)	177.5±20.6 cm (12)	99.9±8.0 cm (12)	59.5±4.6 cm (12)
Far	140.7°±6.4 (24)	130.6±21.0 cm (20)	187.0±40.0 cm (19)	104.6±15.8 cm (20)	70.8±16.1 cm (19)
p-value	0.0902	0.907	0.5353	0.3304	0.1388

p-value calculated for a significance level of 0.05.

Table A.4: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Near and Far zones) by the Under 23 team.

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Near	8.9±0.4 m/s (12)	5.0±0.4 m/s (12)	3.0±0.1 m/s (12)	21.4±3.0 m/s (19)	9.2±1.2 m/s (19)	4.6±0.4 m/s (19)
Far	8.5±1.2 m/s (19)	4.8±0.5 m/s (20)	3.1±0.6 m/s (19)	23.0±3.5 m/s (22)	9.2±1.6 m/s (22)	4.7±0.7 m/s (21)
p-value	0.0465*	0.0837	0.4374	0.082	0.8036	0.6835

p-value calculated for a significance level of 0.05.

Appendix B

Table B.1: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Left and Right zones) by the Under 23 team.

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Left	132.2°±6.3 (24)	127.3±14.9 cm (24)	197.2±27.2 cm (24)	114.6±16.9 cm (24)	75.7±11.5 cm (24)
Right	137.6°±7.2 (27)	136.9±16.3 cm (27)	201.3±36.9 cm (27)	121.0±18.7 cm (26)	77.8±10.1 cm (26)
p-value	0.0133*	0.0455*	0.3802	0.0968	0.4316

p-value calculated for a significance level of 0.05.

Table B.2: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Left and Right zones) by the Under 23 team.

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Left	8.7±1.1 m/s (24)	5.1±0.8 m/s (24)	3.4±0.5 m/s (24)	22.4±3.0 m/s (24)	9.7±1.9 m/s (24)	4.3±0.6 m/s (24)
Right	89.1±1.4 m/s (27)	5.5±0.8 m/s (26)	3.5±0.4 m/s (26)	21.5±3.2 m/s (27)	9.3±1.9 m/s (26)	4.5±0.5 m/s (25)
p-value	0.326	0.2167	0.3301	0.1653	0.454	0.2696

p-value calculated for a significance level of 0.05.

Table B.3: Angle and distance traveled differences (Last stride length, foot, knee, and hip distances) during the performance of Free Kicks in different pitch zones (Left and Right zones) by the B team.

			Distance		
	Angle	Last Stride Length	Foot	Knee	Hip
Left	136.2°±5.6 (29)	124.6±13.5 cm (19)	177.5±32.7 cm (18)	102.1±11.6 cm (19)	66.7±12.7 cm (18)
Right	141.6°±6.3 (24)	132.9±22.0 cm (13)	191.3±34.1 cm (13)	103.8±16.3 cm (13)	66.0±16.0 cm (13)
p-value	0.0023*	0.3278	0.2935	0.7443	0.8413

p-value calculated for a significance level of 0.05.

Table B.4: Movement speed and maximum velocity of the three analyzed joints (foot, knee, and hip) during the performance of Free Kicks in different pitch zones (Left and Right zones) by the B team.

	Speed			Max Velocity		
	Foot	Knee	Hip	Foot	Knee	Hip
Left	8.5±0.9 m/s (18)	4.9±0.4 m/s (19)	3.1±0.3 m/s (18)	21.7±3.7 m/s (19)	8.7±1.4 m/s (19)	4.6±0.5 m/s (18)
Right	8.9±1.1 m/s (13)	4.8±0.5 m/s (13)	3.0±0.6 m/s (13)	22.8±3.0 m/s (22)	9.6±1.3 m/s (22)	4.7±0.6 m/s (22)
p-value	0.3563	0.5612	0.2262	0.5739	0.0689	0.3261

p-value calculated for a significance level of 0.05.