Introduction and State of the Art

The understanding of human motion has, for a long time, involved researchers from various scientific disciplines: biomechanics, functional anatomy, physiology and neuroscience, etc. Although these different areas of concern are important in order to completely understand human motion, it is not realistic to try to cover all these aspects at the same time. This book deliberately tries to focus on the kinematic aspects, that is to say the quantified description of the human body movement, without looking into understanding the causes or its controlling factors.

The aim of this book is to provide the basis, both from an experimental point of view and a theoretical point of view, in order to understand the kinematics of human motion. Thus, after a quick overview of the contributions made to the analysis of human motion by several famous pioneers and a review of current needs in different domains, Chapter 2 presents the main types of system available on the market to analyze movement (beginning with their main advantages and disadvantages), and then describes the principle and implementation of the one that is currently most widely used: the optoelectronic system based on passive markers. The theoretical bases needed to calculate joint kinematics
are then explained in Chapter 3, pointing out the standardization proposed on an international scale to present parameters of motion. Chapter 4 is then dedicated to the delicate problem of measurement errors and their management, and several clinical applications of motion analysis are outlined in Chapter 5.

Following this brief presentation of the general outline of this book, we will briefly present the most significant historical benchmarks in the understanding of human movement before focusing on the different domains in which motion analysis is currently found.

1.1. Historical benchmarks

In ancient Greece, the study of human movement was very often intrinsically linked to that of animal movement. The philosopher Aristotle (383–321 BC) also published one of the first known texts on biomechanics, describing how animals walk, as well as presenting detailed observations of patterns of human motion when performing different tasks [ARI 14].

Art was a strong driver for increasing the knowledge about human motion. In particular, Leonardo da Vinci (1452–1519) was convinced of the need, for an artist or a painter, of having an in-depth knowledge of anatomy. He emphasized that “the science of mechanics is so noble and useful when compared with all other sciences that all living organisms may have the possibility of moving according to these laws”. Da Vinci, therefore, associated dissection and mechanics, movement and function, to find the closest possible link between anatomy and motion, which he thought of essential in order to represent it pictorially [LE 08] (see Figure 1.1(a)).
Figure 1.1. Collection of drawings by Leonardo de Vinci: a) detailed human anatomy, b) a man climbing a step and c) a man climbing a ladder, according to [SUH 05]

He studied, in particular, problems associated with the equilibrium of human posture (Figure 1.1(c)) and several daily actions including sitting down, getting up, climbing a ladder, etc. It is even more impressive to see that, through
such details, he had already described the successive stages of motion, so that they could be better represented (Figure 1.1(b)).

Giovanni Alfonso Borelli (1608–1679) is also widely renowned as one of the pioneers of the study of human movement. By applying the mechanical principles proposed by Galileo Galilei (1564–1642), in an attempt to explain the movements of animals and humans in his famous work *De Muto Animalium* [BOR 89], Borelli is often considered as the “father of biomechanics”. He was, however, the first to understand the importance of lever arms of the musculoskeletal system in the production of movement (Figure 1.2).

![Figure 1.2. Drawings of G.A. Borelli, according to [BOR 89]](image)

The next pioneers were the Weber brothers, who were the first to establish the trajectory of the center of mass during walking [WEB 92].
Figure 1.3. Study of human walking according to [WEB 92]

Jules-Etienne Marey, a French physiologist (1830–1907), was also incredibly interested in animal and human locomotion [MAR 73, MAR 94]. Marey and his assistant Georges Demeny developed measurement tools in an attempt to establish physiological laws of movement (Figure 1.4).

Figure 1.4. a) A runner equipped with instruments to measure his movement, including b) a shoe especially designed to measure the duration and phases in contact with the ground. c) A trotting horse equipped with instruments to measure the locomotion of its limbs, including d) a hoof designed to measure the pressure that the ground exerts on the hoof, according to [MAR 73]
In particular, they developed the chronophotograph, which allows successive stages of movement to be superimposed onto a single photograph (Figure 1.5(a)), and allowed the first quantitative studies by combining this procedure with wearing a clever black piece of clothing on which the white lines materialized the segment axes (Figure 1.5(b)).

During this period, Eadward Muybridge (1830–1904), an American photographer of British origin, was inspired by the work of Marey. He developed the zoopraxiscope, a projector that recomposed movement by rapidly displaying successive stages (Figure 1.6).
Anecdotally, there was some controversy at that time with regard to whether or not the foot of a galloping horse ever touched the ground. To resolve this issue, Muybridge used 24 photographic devices along a riding track, which were triggered from a distance by strained threads, and obtained his famous snapshot (Figure 1.7), which confirmed the theory of Marey, who stated that there was in fact a moment where all four legs were off the ground in gallop [MUY 57].

Wilhelm Braune (1830–1904) and his student Otto Fischer (1861–1917), both German anatomists, were also inspired by the work of Marey, and were the first to develop experimental studies of human walking, in particular in order to measure the evolution of the center of gravity in space [BRA 87].
Figure 1.7. The “Daisy gallop”, according to [MUY 57]

Figure 1.8. Instruments specifically developed to measure human walking, according to [BRA 87]
Here, we are already close to the three-dimensional (3D) analysis of movement that we find today, due to the incredible growth of technological development. After this quick historical overview, we are now going to look at the large subject areas in which the analysis of movement is currently found.

1.2. Current needs in different domains

A Motion Capture system (MoCap) is a system that is capable of restoring the position and orientation of a moving object. In particular, these systems are not only destined for the entertainment market (cartoons, special effects, video games, etc.), but also to meet other needs. In fact, these systems can be used for ergonomic purposes: to improve the comfort and safety when a human being interacts with the environment; in humanoid robotics: to improve the integration of these anthropomorphic robots in extremely varied applications; in sports, to improve the performance of athletes; or even in clinical contexts, to improve diagnoses, assess treatments or design new prosthetic models.

1.2.1. Simulation of movement in ergonomics

In industry, musculoskeletal disorders, for example, are prevalent (a literature review found that 22% of people were suffering or had suffered from this type of disorder in Europe in 2007 [MUS 11]) and proactive ergonomic approaches are becoming widely used in order to assess each job post in terms of feasibility, safety and efficiency of different tasks. A complex analysis is often required to improve job posts or processes, and digital human models are widely used to perform these analyses.

The digital human models are most often used in the conception of vehicles. In this domain, the needs to which
this industry must respond are, in fact, constantly evolving: the user requirements in terms of ethics, performance and safety can now be met, and their demand is now based on other criteria including comfort of use of a vehicle or ease of getting in or out [WEG 07]. The role of ergonomics in the design stage has thus become essential. Until recently, ergonomic assessments used large physical models and were based on the expertise of ergonomists and the feelings of a rather large panel of testers. The freedom with which ergonomists had to develop was, therefore, limited by time and cost of manufacture or prototypes and by the fact that they were involved in the final stages of development, once the design had been validated. The successful integration of ergonomic measures earlier in the design process involves making the analysis and traditional computer-assisted design tools consistent, which require the development of human numerical models close to reality, capable of interacting with a virtual environment, and assessing the quality of this environment. These models, which are capable of taking on the roles of pilots, passengers or maintenance operators, are particularly used to assessing the field of vision, the volume of traffic or even the discomfort caused by the execution of a given task.

![Figure 1.9. Illustration of human models. a) Ramsis](http://www.dhergo.org/) and b) Jack (Siemens Technomatix)
One of the challenges when simulating movement in ergonomics is the redundancy of the human body, both in the kinematic and muscular sense (approximately 240 degrees of freedom, motorized by 630 muscles, etc.). Also, simulation must choose, from a set of possible movements, the solution that corresponds to the behavior that the user would adopt under the test conditions. For this, several approaches are feasible. One of the approaches is based on a large database of movements, made possible due to the fast development of movement analysis systems. It involves guiding the simulation using experimental data collected during a similar scenario in terms of the anthropometrics of the subject and characteristics of the task analyzed. However, in this case, it is difficult to extend these simulations beyond the domain of the experimental campaign. To solve this issue, an alternative approach combines the use of experimental data and a priori knowledge of movement control strategies [WAN 08], strategies whose identification again requires experimental observations. The interested readers can find a description of the developments and applications of human numerical models in [DUF 09].

1.2.2. The command of humanoid robots

An anthropomorphic system, or a humanoid robot, is characterized by its sheer complexity, mainly expressed in terms of degrees of freedom, and it permits us to perform a wide variety of applications. Despite some attempts to imitate the human anatomy (such as the robot Kenshiro created by the Japanese laboratory Johou Systems Kougaku), humanoid robots have anthropometric characteristics that are quite different from those of humans, but unlike digital human models used in ergonomics, the technical specifications of their polyarticular structure and servomotors that generate their movements are known. In this context, the main objective is not to accurately reproduce a human motion but instead that the robot is
capable of carrying out a given task (locomotion, prehension and manipulation of tools) by taking the physical reality of the surrounding environment into account, even if it adopts a different strategy to that which would have been naturally chosen by a human. There are different categories of humanoid robots: androids, specialized robots to replace humans in a specific and/or repetitive task, experimental robots that are used to replace humans in dangerous or inaccessible environments, and most recently, service robots such as those designed to assist people who have lost some autonomy. With the upright posture being particularly unstable, dynamic being an adjective of study here in the control of humanoid robots’ actions [ALG 12]. The complex morphology of this system makes possible different body segments to contribute to equilibrium, but this richness induces problems with modeling and command, which require an analysis of movement and postural coordination in humans to extract relevant data for the command of robots.

Figure 1.10. Humanoid robot Romeo (http://projetromeo.com/)
1.2.3. The analysis of sporting movements

The objective here is to improve sporting performance and/or avoid risk associated with the practice of sports. The 3D analysis of sporting movement is a considerable development, both for the athlete when designing his/her targets, and for the trainer during the technical analysis and training of athletes, as well as for the clinician to better understand the technopathies during diagnosis and prophylaxis or simply when monitoring neuromotor reprogramming after injury. Due to the use of movement analysis systems together with the implementation of biomechanical methods, it is possible to accurately describe the most complex sporting actions, which allow us, for example, to test the relevance of a particular sporting action to that of a champion, or the quality of different materials.

Figure 1.11. Analysis of the movement of a fencer: taken from [GÖP 09]

Recent developments in movement analysis systems made possible high-frequency recordings, and it is now even possible to envisage taking in situ measurements, essential elements in this application domain. However, systems using sensors or markers on the subject are often deemed to be too
intrusive, that is to say that they interfere too much with movement, for the analysis of sporting actions.

1.2.4. Clinical applications of movement analysis

Currently, walking is by far the most widely studied activity in clinics. Video is easy to implement routinely in clinics and makes an initial assessment of walking possible. However, after visualizing overall walking, in different planes (front and side), at normal speed or in slow motion, it is worth carrying out a systematic interpretation of a representative gait cycle by pausing the image at each characteristic time (end of swing/initial stance phase, mid-stance and terminal stance and mid-swing). This analysis, besides its long processing time, also has the drawback of remaining qualitative, or even subjective, and therefore depends on the expertise of the operator.

Tools that are simple to use facilitate an initial objective assessment by providing access to the spatiotemporal parameters of walking (e.g. GaitRite® mat), useful in the functional assessment of certain pathologies, such as Parkinson’s disease [BRA 10], but they are still too limited for analyzing complex walking problems.

Quantitative gait analysis (QGA) is a full exam, recently introduced in France in the common classification of medical procedures. (CCMPs) with the code NKQP003, associated with the title “three-dimensional analysis gait analysis”. QGA provides four types of data, associated with the different measurement systems used: spatiotemporal and kinematic data (MoCap systems), dynamic data (force platforms) and electromyography data. The success of this type of QGA is a full exam has been widely demonstrated [WRE 11], particularly when determining what surgical operation is needed in infants suffering from cerebral palsy, where it has allowed doctors to modify their surgical
indications, in particular improving the development of “multi-site” surgery [DE 97]. Apart from aiding in decision-making, the comparison of successive QGA results obtained from experiments conducted on the same patient makes possible for a treatment to be assessed (e.g. ligament reconstruction, total hip or knee prosthesis) Broström E.W., et al. [BRO 12b], or even the alignment of lower limb prostheses [LUC 10].

Figure 1.12. QGA at the Orthopedics Institute at Children’s Hospital Colorado (http://orthopedics.childrenscolorado.org/)

Other clinical applications will be presented in more detail in Chapter 5 of this book.

After this overview of different areas in which movement analysis is found, we will focus on the measurement methods for data acquisition.