

Understanding Human Motion: A Historic Review

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Abstract. Understanding human motion is based on analyzing global motion patterns, rather than on studying local patterns such as hand gestures or facial expressions. This introductory chapter reviews briefly (by selection, not by attempting to cover developments, and with a focus on Western History) people and contributions in science, art, and technology which contributed to the field of human motion understanding. This review basically stops at the time when advanced computing technology became available for performing motion studies based on captured image data or extensive (model-based) calculations or simulations.

1 Introduction

Interest in human motion goes back very far in human history, and is motivated by curiosity, needs or methods available at a time. For example, a biomechanical perspective is characterized by the “need for new information on the characteristics of normal and pathological human movement” [36]. It is also possible to outline disciplines of science (e.g., mathematics) or arts (e.g., paintings, sculptures), relevant to human motion, just to indicate briefly the complexity of the subject. Obviously, different disciplines are interested in different aspects of the subject; biomechanics is, for example, focusing on human locomotion, with less interest in muscle models, and when correcting motion (e.g., of disabled children) by surgery, it will be exactly the opposite.

This chapter attempts to inform about a few developments which are of (somehow) joint interest for computer vision, computer graphics, and biomechanics. Those areas collaborate increasingly in research and developments relevant to human motion.

The following chapter could certainly be more detailed about the historic context of developments in the understanding of human motion at various periods of human history. For example, art was definitely a major driving force for many centuries for specifying human motion (see, e.g., comments on da Vinci below), or Braune and Fischer were (at the beginning of 20th century; see below) among the first to quantitatively measure human motion, but their work was motivated by improving the efficiency of troop movement.

Many mathematical results had been found in the early civilizations of Mesopotamia and Egypt, but a succession of Greek thinkers (starting with Thales, in the -6th century)¹ developed mathematics as a coherent logically organized structure of ideas. We start our review at this period of time.

2 Classical Antiquity

The ancient Greek philosopher Aristotle (−383 to −321) published, besides much other fundamental work, also a (short) text *ΠΕΡΙ ΠΟΠΕΙΑΣ ΖΩΙΩΝ* [3] on the gait of animals. He defined locomotion as “the parts which are useful to animals for movement in place”. The text is very readable, certainly also due to an excellent translation, and it contains discussions of interesting questions (e.g., “why are man and birds bipeds, but fish footless; and why do man and bird, though both bipeds, have an opposite curvature of the legs”), links to basic knowledge in geometry (e.g., “when ... one leg is advanced it becomes the hypotenuse of a right-angled triangle. Its square then is equal to the square on the other side together with the square on the base. As the legs then are equal, the one at rest must bend ... at the knee ...”), or experiments (e.g., “If a man were to walk parallel to a wall in sunshine, the line described (by the shadow of his head) would be not straight but zigzag...”). This text² is the first known document on biomechanics. It already contains, for example, very detailed observations about the motion patterns of humans when involved in some particular activity.

Sculptures, reliefs, or other art work of classical antiquity demonstrate the advanced level of understanding of human or animal motion, or body poses (often in a historic context).

Classical antiquity already used mathematics for describing human poses or motion, demonstrated in art works that we have to consider individual poses as well as collective poses (e.g., in Roman arts, a married couple was indicated by showing eye contact between woman and man, possibly enhanced by a pictured handshake), and showed in general that motion and poses need to be understood in context. Motion was only presented by means of static artwork; the first dynamic presentation of motion was by means of moving pictures, and this came nearly 2000 years later, at the end of the 19th century.

A charioteer with horses four-in-hand traditionally had the horses gallop in a race, where gallop is defined as a certain step-sequence by the horses, also including a period of suspension with no hoof touching the ground. However, until the invention of moving pictures, it was an open question whether such a period of suspension does occur.

In classical antiquity, motion patterns of humans were usually studied in close relation to motion patterns of animals. Indeed, those comparative studies have

¹ We use the astronomical system for numbering years.

² In close relation with Aristotle’s texts *ΠΕΡΙ ΖΩΙΩΝ ΓΕΝΕΣΕΩΣ* (*On the Parts of Animals*) and *ΠΕΡΙ ΖΩΙΩΝ ΚΙΝΗΣΕΩΣ* (*On the Progression of Animals*).

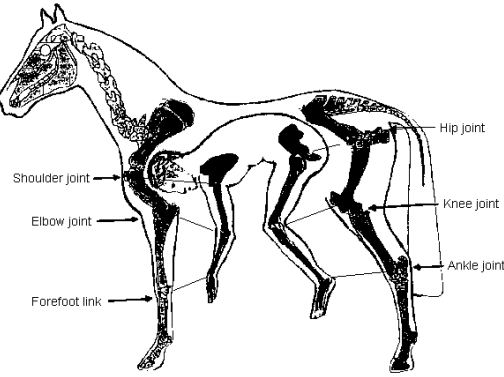


Fig. 1. A modification of a drawing published by W. F. Bartels on www.kutschen.com/Gelenke.htm.

continued to be useful: see Figure 1 illustrating evolutionary relations between joints of humans and horses.

Human motion studies today are basically performed by modeling human (dynamic) shape, and by applying perspective geometry (when understanding recorded image sequences or creating animations). Basics of the geometry of three-dimensional (3D) volumes and, to a lesser extent, also of perspective geometry, date back to classical antiquity [13]. Perspective emerged (at first) from geometrical optics (see, e.g., Euclid’s³ *OPTIKH* (*Optics*), defining visual rays or visual cones), and it received a major stimulus in art of the European Renaissance (see next section).

3 Renaissance

Leonardo da Vinci (1452–1519) stated in his sketchbooks, that “it is indispensable for a painter, to become totally familiar with the anatomy of nerves, bones, muscles, and sinews, such that he understands for their various motions and stresses, which sinews or which muscle causes a particular motion” of a human.⁴ For an example of his modeling of the human anatomy, see Figure 2 on the left and in the middle. In his mirror writing he wrote that “*m c* measures $1/3$ of *n m*, measured from the outer angle of the eye lid to letter *c*” and “*b s* corresponds to the width of the nostril”. However, a few pages later he showed “funny faces”

³ Euclid worked at the Museion in Alexandria (in about -300), writing on mathematics, optics, astronomy and harmony. His “Elements” gives a very detailed study of plane and solid geometry (together with number theory), and it became one of the most influential books ever written. His treatment of geometrical optics formed a basis for the theory of perspective.

⁴ Quotations of da Vinci are translated from [16]. – Today, various books are published on human anatomy specially designed for artists; see, for example, [5].

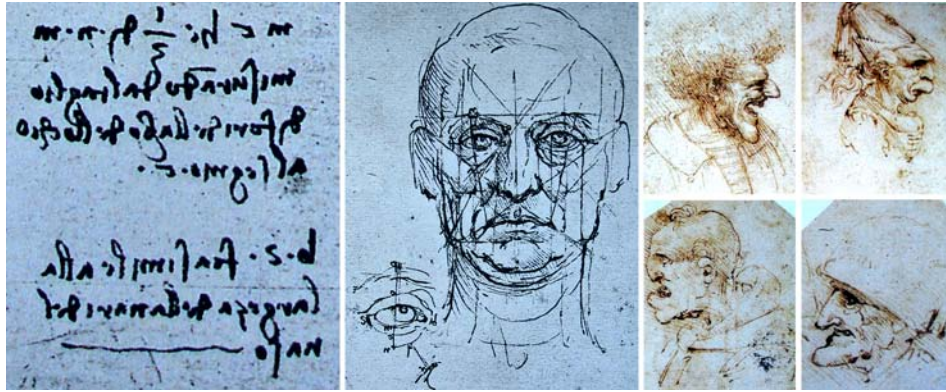


Fig. 2. Fragments from da Vinci's sketchbooks (human faces).

in his sketchbook (for a few, see right of Figure 2), illustrating that a match between model and reality was not always given.



Fig. 3. Drawing in da Vinci's sketchbooks (a man going upstairs, or up a ladder).

Besides very detailed models of the human anatomy, also characterizing special appearances such as parameters of “a beautiful face” (e.g., in his opinion, in such a face the width of the mouth equals the distance between the middle line of the mouth to the bottom of the chin), da Vinci's sketchbooks also contain quite detailed studies about *kinematic trees*⁵ of human motion. For a man going upstairs (see left of Figure 3), he writes: “The center of mass of a human who is

⁵ Today, *kinematic chains* are used for modeling propagations, e.g. of forces, over time along a body part such as an arm or a leg. Da Vinci already considered “divisions”

lifting one foot, is always on top of the center of the sole of foot [on which he is standing]. A human going upstairs shifts weight forward and to the upper foot, creating a counter weight against the lower leg, such that the workout of the lower leg is reduced to moving itself. When going upstairs, a human starts with relieving body weight from that foot which he is going to lift. Furthermore, he dislocates the remaining body mass onto the opposite leg, including the [weight of the] other leg. Then he lifts this other leg and places the foot on the step, which he likes to climb on. Next he dislocates the whole body weight, including that of this leg, onto the upper foot, puts his hand onto his thigh, slides his head forward, and moves towards the tip of the upper foot, quickly lifting the heel of the lower foot. With this push he lifts himself upward, simultaneously he straightens the arm which was resting on the knee. This stretching of the arm pushes body and head upward, and thus also straightens the back which was bended before.”

Next to the drawing, shown on the right of Figure 3, da Vinci wrote the following: “I ask for the weight [pressure] of this man for every segment of motion when climbing those stairs, and for the weight he places on *b* and on *c*. Note the vertical line below the center of mass of this man.”

It is certainly impressive to see the level of detail in modeling human shape or motion, given by da Vinci centuries ago. This was illustrated above just by examples, and a comprehensive biomechanical study about his contributions would be a sensible project.

Michelangelo di Lodovico Buonarroti Simoni (1475–1564) is also famous for his realistically portrayed human motion.

Perspective geometry (required for proper modeling of human motion) was established by means of drawing rules by artists of the Renaissance, such as Filippo Di Ser Brunellesco (1377–1446), Piero della Francesca (1420?–1492), Albrecht Dürer (1471–1528), Raphael (1483–1520), and many others. Perspective geometry also became a mathematical theory, pioneered by Girard Desargues (1591–1661) at the beginning of the Baroque era.

4 Baroque

The scientist Giovanni Alfonso Borelli (1608–1679) contributed to various disciplines. In his “On the Movement of Animals” [8] (published posthumously in two parts in 1680 and 1681) he applied to biology the analytical and geometrical methods, developed by Galileo Galilei (1564–1642)⁶ in the field of mechanics.⁷ For this reason he is also often called “the father of biomechanics” (with Aristotle as a second alternative, see Section 1), or (one of) the founder(s) of the

in those propagations (e.g., from the upper body to both the left and the right leg), here indicated by using the name *tree* rather than *chain*.

⁶ Galileo Galilei became a major founder of modern science, applying analytical and geometrical methods in the field of mechanics, combining theory and experiment.

⁷ Borelli’s great work is almost wholly a study of animal statics, since Newton had not yet developed the mathematics of dynamics.

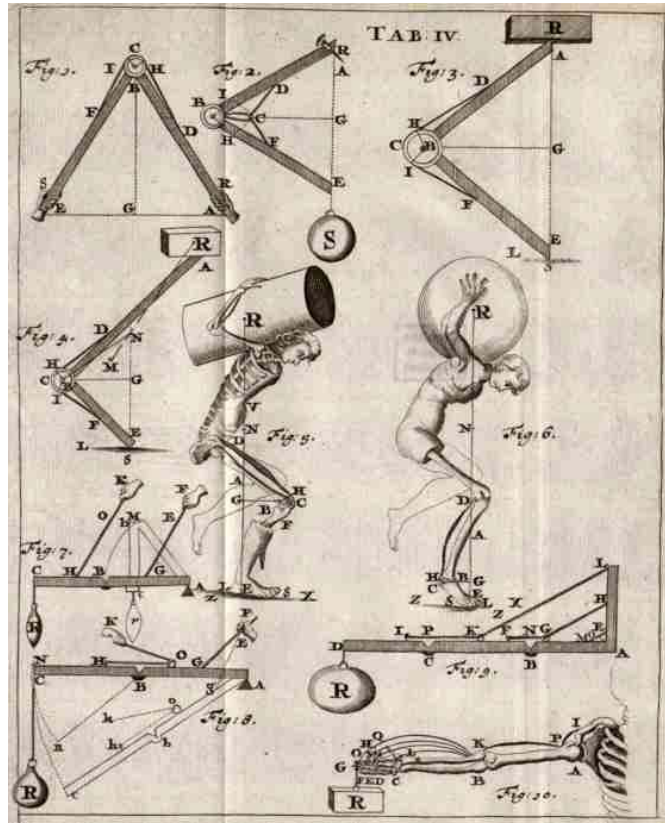


Fig. 4. Copper engraving by Borelli in 1680/1681 (Deutsches Museum, Munich).

Atrochysic School (also called *iatromathematic*, *iatromechanic*, or *physiatric*). A result of basic importance for establishing this school is that the circulation of the blood is comparable to a hydraulic system. This school vanished after some years, but some of the work of Borelli is still worth noting today. He “was the first to understand that the levers of the musculoskeletal system magnify motion rather than force, so that muscles must produce much larger forces than those resisting the motion” [33]. Bones serve as levers and muscles function according to mathematical principles; this became a basic principle for modeling human motion.

Figure 4 shows an example of a drawing from [8]. The physiological studies in this text (including muscle analysis and a mathematical discussion of movements, such as running or jumping) are based on solid mechanical principles. The change from visual (qualitative) observation to quantitative measurements was crucial for the emergence of biomechanics. Borelli also attempted [8] to clarify the reason for muscle fatigue and to explain organ secretion, and he considered the concept of pain.

5 Age of Enlightenment

There seem to be not many important contributions to the study of human motion, between the times of Borelli and the latter half of the 19th century, when chronophotography provided a new tool for understanding motion.

Besides studies on human or animal motion in a narrow sense, the foundation of modern dynamics by Isaac Newton (1642–1727),⁸ including his three laws of motion, was also a very crucial contribution to the understanding of human motion (these laws are formulated here for this case, slightly modified from [42]):

Newton's Law of Inertia. A human in motion will continue moving in the same direction at the same speed unless some external force (like gravity or friction) acts to change the motion characteristics. (This law was already formulated by Galileo Galilei.)

Newton's Law of Acceleration. $F = ma$. A force F acting on a human motion will cause an acceleration a in the direction of the force and proportional to the strength of the force (m is the mass of the human).⁹

Newton's Law of Action-Reaction. A human's motion against a medium (such as another body) is matched with a reaction force of equal magnitude but opposite direction.

All three laws had been discussed already in some sense by Aristotle when considering the motions of a boat. According to Aristotle, “every movement needs a mover”, and his (incorrect !) concept can be expressed as $F = mv$, where v is the velocity [21].

Between the 17th and 19th centuries numerous famous scientists, starting with René Descartes (1596–1650), basically established modern mathematics, including geometrical volumes, analytical geometry, and geometrical algebra. Today's human motion studies benefit from those developments.

We briefly mention Luigi Galvani (1737–1798) and his discovery (1780) of “animal electricity”, which was correctly interpreted (in 1800) by Alessandro Volta (1748–1827) as muscles contracting in response to electric current. Hermann von Helmholtz (1821–1894) invented the myograph in 1852, and he used it to study the propagation of electricity along nerves. He was greatly surprised to find that, in a frog nerve, the electrical signal travelled only 27 metres per second [46].

⁸ Isaac Newton was born on 1642 December 25, in the Julian Calendar which was still used in England. (In the Gregorian calendar the date was 1643 January 3.) He is the most influential of all scientists. He made many major advances in mathematics (including differential and integral calculus), and he applied mathematics with immense success to dynamics, astronomy, optics and other branches of science.

⁹ Newton's statement of the Second Law of Motion is: “The change of motion is proportional to the motive power impressed; and is made in the direction of the right line in which that force is impressed” (the Motte–Cajori translation). Newton's applications of that law shew that “change of motion” means “rate of change of momentum”, and it holds for bodies of varying mass.

The concepts of energy and of thermodynamics were largely developed between 1820 and 1860 by Nicolas Léonard Sadi Carnot (1796–1832), Rudolf Julius Emmanuel Clausius (1822–1888), William Thomson (later Baron Kelvin, 1824–1907), Herman von Helmholtz (1821–1894), and James Clerk Maxwell (1831–1879).

The mathematician Charles Babbage (1791–1871) had, by 1837, invented all of the basic ideas about computers (and many advanced ideas about them). He attempted to construct various mechanical computers, but he did not succeed in completing any working computer. (In 1991, his Difference Engine No. 2 was completed, following his plans - and it worked).

Quantitative physiology was founded in 1866 by the chemist Edward Frankland (1825–1899), who demonstrated experimentally that work done by a human matched the energy of the food consumed [11].

In the 19th century, a variety of toys were made which produced moving pictures. In the 1830s, several inventors developed the *Phenakistoscope*, a disk with several radial slots and successive pictures painted between the slots. When the disk was spun with the pictures on the side facing a mirror, a viewer looking towards the mirror from the blank side of the disk would get momentary views (through the slots) of the pictures in cyclic motion. In the 1860s, several inventors improved that to develop the *Zoetrope*, a rotating drum with slits parallel to the axis. A strip of paper could be fitted inside the cylinder, with slits in the paper fitted to the slits in the cylinder, and with successive pictures printed on the paper between the slits [41, pp.16–20].

A major contribution was the work by brothers Ernst Heinrich Weber (1795–1878), Wilhelm Eduard Weber (1804–1891), and Eduard Friedrich Weber (1806–1871); all three collaborated in their research on physics, human anatomy and locomotion. The latter two published the book [47]. Wilhelm Eduard Weber is famous for the invention of the first electromagnetic telegraph in 1833, jointly with Carl Friedrich Gauss (1777–1855).

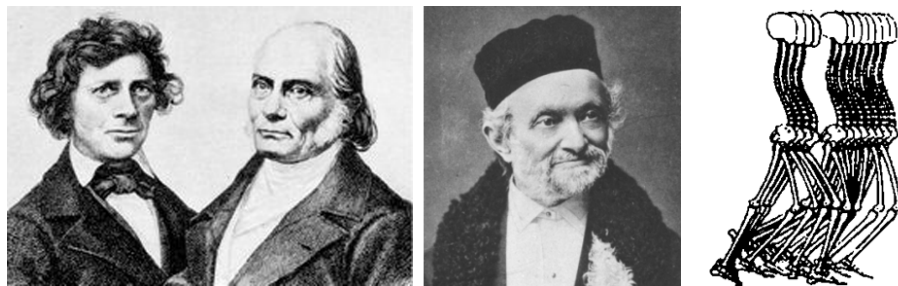


Fig. 5. From left to right: Eduard Friedrich Weber, Ernst Heinrich Weber, and Wilhelm Eduard Weber. Right: calculated picture from [47].

[47] contains “calculated pictures”, see right of Figure 5, pioneering today’s computer graphics. Subsequent phases of human walking are calculated using differential equations, and visualized by drawings using perspective projection.

[47] analyzed human gait and provided a theory of locomotion, including the prediction of a “walking machine” (with two, four, or more legs, depending on terrain difficulty), moved by steam. In fact, movement control of today’s multi-legged robots depends on solutions of PDEs (partial differential equations). The Weber brothers were the first who studied the path of the center of mass during movement.

The mathematician Pafnyutii L’vovich Chebyshev (1821–1894) advanced greatly the theory of mechanical linkages. His inventions include a wheelchair driven by crank handles, and a model of a 4-leg walking machine. Such “walking machines” might have inspired Mrs. Edmund Craster (died 1874) to write her poem *The Centipede*:

The Centipede was happy quite,
Until the Toad in fun
Said ‘Pray, which leg goes after which?’
And worked her mind to such a pitch
She lay, distracted, in the ditch
Consid’ring how to run.

6 Chronophotography

The French astronomer Pierre Janssen (1824–1907) used on 8 December 1874 a multi-exposure camera (of his own invention) for recording the transit of Venus across the Sun. His “clockwork ’revolver’ took forty-eight exposures in seventy-two seconds on a daguerreotype disc. Janssen’s work in turn greatly influenced the chronophotographic experiments” [48] of the French scientist Etienne-Jules Marey (1830–1904); see left of Figure 6 for a photo of himself. He was interested in locomotion of animals or humans. In his book [31] he reported about motion studies, where data had been collected by various instruments; see Figure 7.



Fig. 6. Left: E.-J. Marey. Right: an 1882 photo by Marey.

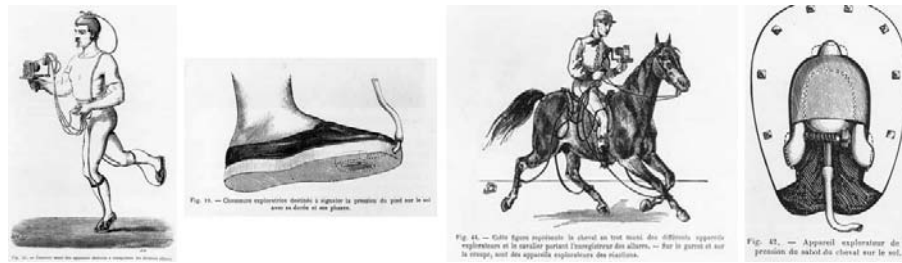


Fig. 7. Left: a runner with instruments to record his movements, including a shoe to record duration and phases of ground contact. Right: a trotting horse with instruments to record the horse's leg locomotion, including an instrument for measuring the ground pressure of a hoof [31].

His interests in locomotion studies led him later to the design of special cameras allowing a recording of several phases of motion in the same photo. Figure 6, right, shows a flying pelican recorded by him around 1882. Marey reported in a 1890 book about locomotion of birds, also using his photographs for illustration and analysis. Later he also used movies (with up to 60 pps in good quality), which was influential pioneering work for the emerging field of cinematography. Figure 8 illustrates his work reported in the book [34]. Also see [10] (shortlisted in 1994 for Britain's Kraszna-Krausz award).

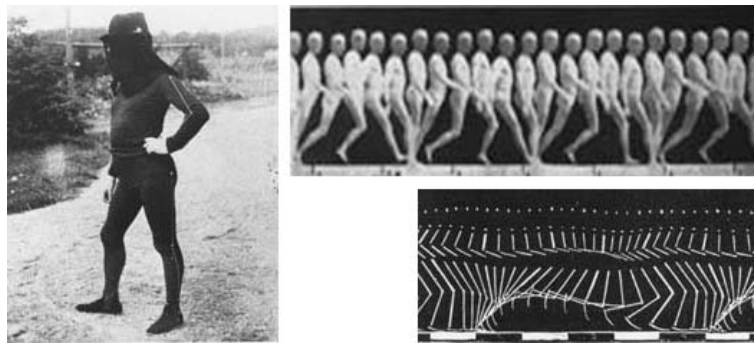


Fig. 8. Left: a man in a black dress; limbs are marked by white lines. Right, top: a chronophotograph of a striding man dressed partially in white, and partially in black. Right, bottom: white lines in a chronophotograph of a runner [34].

The British-born Eadweard Muybridge (1830–1904) became a renowned photographer after he emigrated to the USA. Inspired by Marey's recording of motion [29], and by a disputed claim that a galloping horse may have all four hooves off the ground, in 1878 he set up a series of 12 cameras¹⁰ for recording fast

¹⁰ In 1879, he increased that to 24 cameras.

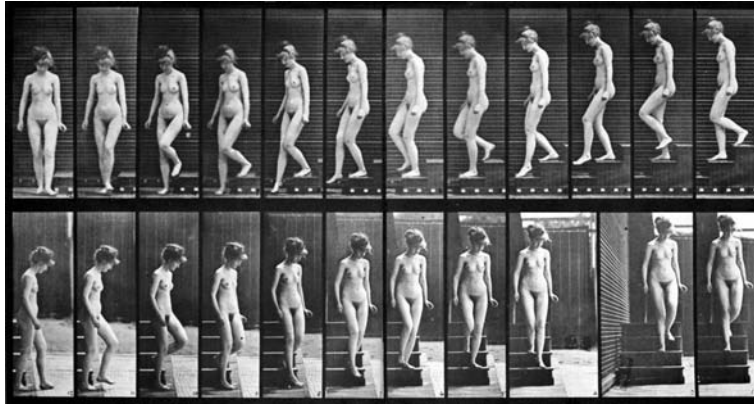


Fig. 9. Woman walking downstairs (Muybridge, late 19th century).

motion alongside a barn, sited on what is now the Stanford University campus. His rapid sequence of photographs of a galloping horse did shew all four hooves off the ground for part of the time [41, p.21] [37]. He invented a machine for displaying the recorded series of images, pioneering motion pictures this way. He applied his technique to movement studies. The human subjects were typically photographed nude or nearly nude, for different categories of locomotion; see Figure 9.

Muybridge's motion studies, based on multiple images, included walking downstairs, boxing, walking of children, and so forth. They are often cited in the context of the beginning of biomechanics, and they were definitely very influential for the beginning of cinematography at the end of the 19th century. Movies were shot in several countries, shortly after his successful demonstrations of "moving pictures".

A third famous representative of chronophotography was the German inventor Ottomar Anschütz (1846–1907) whose 1884 photographs of gliding flights of storks inspired Otto Lilienthal's design of experimental gliders. One of Anschütz's inventions is a $1/1000$ th of a second shutter. Earlier than Muybridge, he invented in 1890 a machine (called *Tachyscop*) for the first moving pictures. It was similar to a *Zoetrope* but used photographs lined up in a cylinder, which could be seen through a slot (e.g., a walking man, a walking woman, the gallop of a horse, and a flying crane). Anschütz also took photos of the first flights of Lilienthal in 1893 and 1894; see Figure 10.

Less known, but also a pioneer of the early days of human motion capturing, was Albert Londe (1858–1917) [48]. Londe constructed a camera, fitted with (at the beginning of his studies) 9 lenses arranged in a circle, and used this camera to study the movements of patients (at La Hôpital de la Salpêtrière in Paris) during epileptic fits.

The work by Marey and Muybridge was also of great influence in the arts [15]. Figure 11 shows on the left a detail of one of Muybridge's plates, showing a



Fig. 10. Lilienthal's flight, Maihöhe 1893, photographed by O. Anschütz (Otto Lilienthal Museum, Germany).

female with a handkerchief. Duchamp points to Marey for origins of his *Nude Descending a Staircase*, and Picasso points to one of Muybridge plates, entitled *Dropping and Lifting of a Handkerchief* (1885), for origins of his *Les Femmes d'Alger*. The English painter Francis Bacon (1909–1992) even compared the importance of Muybridge for his artistic development with that of Michelangelo [15].



Fig. 11. From left to right: detail of one of Muybridge's photographic plates, Pablo Picasso's *Les Femmes d'Alger* (1907), Marcel Duchamp's *Nude Descending a Staircase*, and Hananiah Harari's *Nude Descending a Staircase*.

7 Human Motion Studies in Biomechanics

In the latter half of the 19th century, Christian Wilhelm Braune (1831–1892) and Otto Fischer (1861–1917) started with experimental studies of human gait (e.g., for determining the center of mass), which resulted in the development of prosthesis. Less known, Gheorghe Marinescu (1863–1938) produced in 1898 (with the help of operator Constantin M. Popescu) the first scientific movie “Walking disorders in organic hemiplegia”; see [32].

In the 20th century, biomechanics developed into a discipline of science, establishing its own research programs. The French reformer (and ‘work physiologist’)

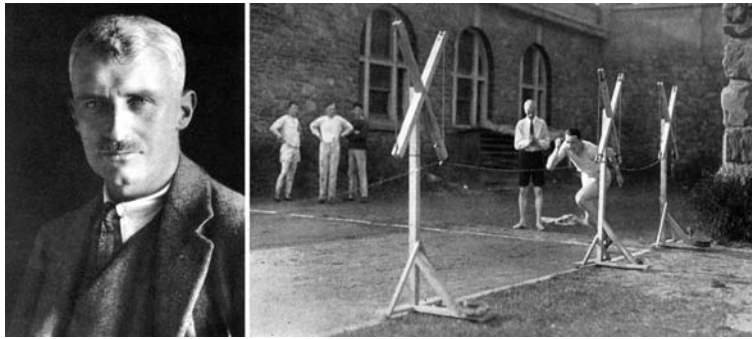


Fig. 12. Left: A. V. Hill. Right: Testing the acceleration of sprinters by Hill at Cornell University, Ithaca, NY [23]. “The large coils of wire were used to detect a magnet worn by the runner as he sprinted past them. Velocity and acceleration were calculated by knowing the distance between the wire coils.” [6].

Jules Amar (1879–1935) published in 1914 the very influential book [2], which soon after defined the standards for human engineering in Europe and the United States. The technology of cinematographic analysis of sprint running allowed a new quality in research (note: the flicker-fusion rate of the human eye is only about 12 Hz); see, for example, papers [17, 18] by Wallace O. Fenn (1893 – 1971), who became the president of the American Physiological Association. Graduate programs in biomechanics developed in the United States in the 1940s. Starting with the 1950s, biomechanics became a worldwide discipline for physical educators, especially in the context of sports. Helmholtz’s myograph was developed into the electronic electromyograph, for measuring the electric activity of muscles.

The book [7] by Nicholas Bernstein (1896–1966) pioneered the areas of motor control and coordination. He studied the spatial conception of the degrees-of-freedom problem in the human motor system for walking, running or jumping. Archibald Vivian Hill (1886–1977) was convinced by F. G. Hopkins (Nobel Prize in Physiology or Medicine, 1929) to “pursue advanced studies in physiology rather than mathematics” [43]. Hill investigated the efficiency and energy cost in human movement (see, e.g., [24]). Based on his solid background in mathematics, he developed mathematic “models describing heat production in muscle, and applied kinetic analysis to explain the time course of oxygen uptake during both exercise and recovery” [43]. His research initiated biophysics [25]. Hill shared the 1922 Nobel Prize in Physiology or Medicine with the German chemist Otto Meyerhof. Hill was honored for his discoveries about the chemical and mechanical events in muscle contraction [22].

Research in computerized gait analysis is today widely supported by marker-based pose tracking systems (see Figure 13), which have their origins in the work by G. Johansson [26] (see Section 9). Basically, the camera systems used are fast (e.g., 300 Hz or more), but recorded images are normally restricted to binary information, showing positions of markers only. Computer vision already helped



Fig. 13. Gait laboratory of The University of Auckland (in 2000). Left: walking subject with markers. Middle: walking area (top) and one of the fast cameras (bottom). Right: generated animated 3D stick figure (top) and camera calibration unit (bottom).

to create 3D body models for gait analysis (e.g., by using whole-body scanners, based on the principle of structured lighting, or by applying photometric stereo [4]). The increasing availability of high-speed cameras supports the development of marker-less motion tracking systems (e.g., [40]), overcoming the apparent restrictions of marker-based systems.

For a review on past and more recent work in biomechanics, see [44]. Recent textbooks are, for example, [50, 51], or other book publications by Human Kinetics. [36] reviews markerless motion capture for biomechanical applications; see also Chapter ?? in this book. Chapter ?? is about motion variations between clinical gait and daily live, and Chapter ?? on studies to support the optimization of human motion.

8 Human Motion Studies in Computer Graphics

Computer animation of human walking is a major area of interest in computer graphics. Compared to biomechanics, the discipline emerged “recently”, namely about 50 years ago with the advent of the computer.¹¹

Basically, a computer graphics process starts with defining the models used. Figure 14 illustrates three options. Tracking markers (see previous section) allows to generate a stick figure, which may be based on general assumptions into a volumetric model (e.g., defined by cylindric parts, or a generic body model of a

¹¹ The first working computers were built during World War 2 (with the first COLOSSUS operating at Bletchley Park in December 1943), and now computers have become essential tools in most branches of science, including studies of human motion.

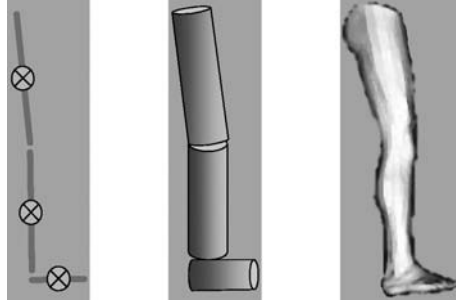


Fig. 14. Three options for modeling a leg: stick figure (left), simple geometrical parts (middle), or a (generic) model of the shape of a human leg.

human). Then the ways are specified how to present those models, for example rendered with respect to given surface textures and light sources in form of an animation, within a synthesized scene, or just against a monochromatic background (see Figure 15 for an example of recent graduate student projects; for more complex animations see commercial products of the movie or game industries, which are major forces pushing for progress in animated human motion).

Static models of moving humans, or dynamic 3D poses, are generated by applying various means. For static whole-body modeling, this can be achieved, efficiently and accurately, by structured lighting or encoded light (e.g., Gray codes) for static bodies (see, e.g., [28]). LEDs, marker-based multi-camera systems (see



Fig. 15. Frames of various animations of human movements [20]. The clip illustrated on the lower left allows to compare synthetic and real human motion.

Figure 13), or silhouette-based generic 3D model tracking (e.g., [40]) are options for capturing data about movements of a human.

For recent books, addressing human motion studies in computer graphics (and in computer vision), see [19]. Sun and Metaxas showed in [45] how gait, captured on even ground, can be used to generate realistic motion on uneven terrain. Chapter ?? discusses realistic modeling of human motion. Chapter ?? is about the importance of human motion analysis for character animation. Chapter ?? provides deformable models for a possible option to represent motion.

9 Human Motion Studies in Computer Vision

Computer vision exists for about the same time as computer graphics. Instead of only capturing image sequences, to be analyzed by a human observer, now those sequences are digitized, and computer programs are used for an automated analysis of the sequence. As illustrated by Figure 8, Marey already used simplifications such as white skeletal curves on a moving human. Braune and Fischer [9] attached light rods to an actor’s limbs, which then became known as *Moving Light Displays* (LEDs). Gunnar Johansson [26, 27] pioneered studies on the use of image sequences for a programmed human motion analysis, using LEDs as input. These very limited inputs of information allow an interesting analysis, for example with respect of identifying a particular person.

Motion analysis in computer vision has to solve two main tasks, detecting correspondences between subsequent images, and tracking of an object within a sequence of images. This can be based on different methodologies, such as tracking 2D features at a local (e.g., corners) or global level (e.g., silhouettes, after a “proper” segmentation of images), or tracking based on projecting a generic 3D model (of a human) into the scene (see Figure 17).

For reviews on human motion studies in computer vision, see [1, 35]. The use of LEDs in computer vision is reviewed in [14]. For a recent collection of papers, also covering human motion in computer vision, see [38]. Human motion studies

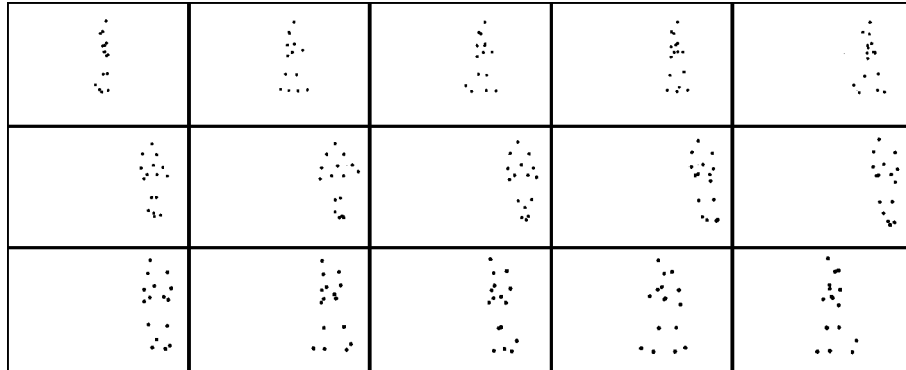


Fig. 16. A sequence of 15 LED frames, extracted from an animation on [30].



Fig. 17. Human poses are tracked using a generic 3D model of the upper human body; the figure shows the backprojection of the recorded 3D motion into the original 4-camera image sequence, also demonstrating model movements of occluded body parts [40].

in computer vision have been already a subject of an international workshop [49]. As an example of a recent “landmark”, we cite [52], discussing in depth the recognition of people based on gait.

This book contains a basic Chapter ?? on various models for human motion and Chapter ?? which reviews human motion analysis. The understanding of human motion from video, and the tracking of moving people, is the subject in Chapters ?. Special issues when tracking clothed people are discussed in Chapter ?. The recognition of human actions is reported in Chapter ?. Chapters ? are about human motion studies in the context of computer-human interaction.

The Chapters ? provide information about theoretical areas which have proved to be of use for human motion modeling or understanding (Geometrical algebra, simulated annealing, manifold learning). Finally, Chapter ? discusses the application of human motion studies in a particular application (dummy movements and crash test analysis). The application of motion analysis for cardiac motion studies is reported in Chapter ?.

10 Conclusions

This review certainly proves that studies on human motion were and are interdisciplinary (from the beginning, which was about 2000 years ago). This book aims at contributing to deeper interactions between biomechanics, computer graphics, and computer vision (already existing at advanced levels in some institutes,

see, e.g., [12, 39]). Certainly, further areas are of relevance, with biophysics or mathematics as major contributors, or medicine (e.g., rehabilitation technology), robotics (e.g., studies on passive dynamic walking), or sports sciences (e.g., modeling of athlete motion) as important areas of application. However, the book was planned for the time being to remain focused on those three areas, but future development of human motion studies will certainly also benefit from interactions with neurology (e.g., neural control mechanisms for motion), cognitive sciences (e.g., selective attention to understand motion), health exercises (i.e., not just focussing on sports, but also on recreation), and so forth.

Basic concepts for biomechanical studies of human motion were already developed by 1687, when Isaac Newton published his three laws of motion. Basic mathematic tools for human motion studies were already provided in mathematics by the end of the 19th century. The start of photography in the 19th century led to the documentation of human motion, starting at the end of the 19th century. The advent of the computer, and of digital technology in general in the latter half of the 20th century finally provided the tools for analyzing human motion based on digitized image sequences, and for animating or studying human motion using extensive calculations and detailed models of human locomotion.

There is a general demand in more in-depth studies on locomotion (e.g., also on gait disorders). A future major qualitative advance in the area of human motion studies is expected with the widespread use of high-speed, high-resolution, and light-sensitive cameras for recording and analyzing human motion, and at the time when human motion analysis becomes an integrative approach in medical treatments.

There is furthermore a continuous strong progress in computer vision and graphics. Computer graphics, with animations and game applications, are a major force to simplify motion understanding and capturing into integrated vision and graphics systems. Recent applications are already manifold, also including identifications of persons (i.e., by gait patterns), motion advice (e.g., for learning golf), documenting particular performances (e.g., 3D models of dancing), or multimedia presentations (e.g., mapping of recorded motion into a prepared image sequence).

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Appendix: A few Definitions

Biomechanics studies living organisms at different levels – from molecular to macroscopic level – as mechanical systems (i.e., internal and external forces acting on the moving body, and effects produced by these forces).

Computer Graphics generates digital pictures or animations for visualizing real or synthetic scenes, objects, or processes.

Computer Vision analyzes 3D scenes, objects, or processes based on captured images, with the purpose of modeling or understanding the pictured scenes, objects, or processes.

Chronophotography ("pictures of time") is applied science (used mainly in the second half of the 19th century), using photography for studies of changes in time.

Dynamics is concerned with the effects of forces on the motion of objects

Locomotion is (in biology) an autonomous motion of an individual (human, bird, fish, and so forth), considered to be defined by a sequence of patterns composed by anatomic parts. Locomotion patterns can be classified into categories such as walking, jumping, swimming, and so forth.

Kinematics is a subfield of biomechanics studying movements with respect to geometrical aspects, without references to its physic causes (i.e., masses or forces).

Kinesiology denoted (in the United States; this name was first applied to the study of muscles and movements in the first decade of the 20th century by Baron Nils Posse and William Skarstrom) the use of mathematical or mechanical principles for studying human motion (note: basically identical to biomechanics, originally the preferred name for this field in Europe, but now widely accepted worldwide).

Kinetics studies what causes a body to move the way it does, by analyzing the actions of forces contributing to the motion of masses. Subfields are statics and dynamics.

Prosthesis is a field in medicine aimed at artificial replacements of body parts.

Statics is concerned with the analysis of loads (force, moment, torque) on physical systems in static equilibrium (i.e. whose relative positions do not vary over time; for example in inertial motion).