Bipedal Robots

Bipedal Robots

Modeling, Design and Walking Synthesis

Edited by
Christine Chevallereau
Guy Bessonnet
Gabriel Abba
Yannick Aoustin

iSTE

WILEY

First published in France in 2007 by Hermes Science/Lavoisier entitles: *Les robots marcheurs bipèdes : modélisation, conception, synthèse de la marche* © LAVOISIER, 2007

First published in Great Britain and the United States in 2009 by ISTE Ltd and John Wiley & Sons, Inc.

ISTE Ltd
27-37 St George's Road
London SW19 4EU
UK

www.iste.co.uk

John Wiley & Sons, Inc.
111 River Street
Hoboken, NJ 07030
USA

www.wiley.com

Library of Congress Cataloging-in-Publication Data

[Robots marcheurs bipèdes. English]
Bipedal robots : modeling, design and walking synthesis / edited by Christine Chevallereau ... [et al.]
p. cm.
Includes bibliographical references and index.
ISBN 978-1-84821-076-9
1. Robots--Motion. 2. Walking. I. Chevallereau, Christine. II. Title.
TJ211.4.R6313 2008
629.8'932--dc22
2008035231

British Library Cataloguing-in-Publication Data
A CIP record for this book is available from the British Library
ISBN: 978-1-84821-076-9

Printed and bound in Great Britain by CPI Antony Rowe Ltd, Chippenham, Wiltshire.

Table of Contents

Chapter 1. Bipedal Robots and Walking

Chapter 2. Kinematic and Dynamic Models for Walking

Chapter 3. Design Tools for Making Bipedal Robots

Chapter 4. Walking Pattern Generators

Chapter 5. Control

Bipedal Robots: Modeling, Design and Walking Synthesis
Edited by Christine Chevallereau, Guy Bessonnet, Gabriel Abba & Yannick Aoustin

Chapter 1

Bipedal Robots and Walking

1.1. Introduction

Man has always been interested in the relationship between himself and the living world and, more particularly, in understanding how he is different from other animals. Since Antiquity and Aristotle, then during the Renaissance when the first studies were carried out in medicine and physiology, scientists have tried to understand the influence of bipedia on human evolution. In his 1680 publication, *De Motu Animalium*, Borelli [BOR 80] compared different bipedal species, analyzed the importance of pendulous movement and introduced spring-mass models in order to understand walking and running in humans and other bipedal animals.

In the 18th century, Doyon [DOY 66] built a whole ensemble of automats. More recent studies have tried to make parallels between passive human walking and walking executed by prototype robots such as Collins' *Walker* [COL 05] or McGeer's *Straight-legged biped* [MCG 90]. These studies can help us to have a better understanding of the laws needed for commands, stability or the generations of trajectories for future humanoid robots.

Research carried out in biomechanics has enabled us to interpret in more detail the principles of kinetic and potential energy transfer which contribute to defining walking. Tendons and muscles are particularly used during walking and running, acting as actuators but also as shock absorbers. Studies have shown that they temporarily store kinetic energy which is redistributed in the propulsion phases. The simple model of an inverted pendulum mounted on a compression spring placed in the leg can be used to describe running. These studies also show that one of the most influential parameters of stability during running is the start angle between the equivalent virtual leg and the ground [SEY 02]. This angle even seems to be an auto-stabilizing running parameter. These behavioral models have been confirmed by tests carried out at MIT on a one-legged jumping robot [RAI 86].

Biomechanics has also enabled us to design kinematic and dynamic walking and running models from biological systems used during simulations with interactions with the ground, and to determine internal forces. These models have enabled us to develop equivalent methods in the context of robotics.

The number of international research teams working on the subject is steadily rising. The disciplines interested in the theme of bipedal robots are: robotics, but also automatics, mechanics, information technology, biomechanics, medicine (with work on improving orthopedic prostheses and medical rehabilitation) and cinematography (e.g. computer animation). Studies in the field of sport have been concentrated on optimizing training and detecting the limiting constraints of articulations and tendons.

Section 1.2 will present a non-exhaustive overview of the biological and biomechanical approaches to this question. The notions of similarity, the characteristics of energy consumption and mobility are particularly focused on.

Section 1.3 concerns human walking. The structure of lower limbs and their muscles are given in detail to illustrate the specificity of human bipeds. Experimental results obtained from the capture of a walking movement will conclude this section.

Section 1.4 offers a historic overview of the different bipedal robots that have been created worldwide in the past.

Finally, the present day and future applications of robot bipedia will be presented in section 1.5.

1.2. Biomechanical approach

1.2.1. *Biomechanical system: a source of inspiration*

Among the ensemble of living things, only humans and birds use bipedia as a form of locomotion. Certain insects (cockroaches in flight for example), reptiles (e.g. lizards, geckos and monitor lizards) and mammals (e.g. primates, bears, mongooses and rats) use bipedia in exceptional cases. In the history of species, bipedia appeared during the Mesozoic periods among a large number of dinosaur reptiles. The anatomic structure of the legs of these animals is very similar, consisting of a thigh, a leg and a foot. Each lower limb has three main articulations: the hip, the knee and the ankle. The hip is a spherical link with three degrees of mobility. The knee is a link with one or two degrees of freedom (DoF). The ankle brings together two main mobilities. An important difference is the relative length of the foot and its average position during walking which can perceptibly modify the extreme values of joint angles.

Physiologists and anatomists have developed the laws of similarity from measurements taken from animals and humans. In the 1980s, the comprehensive work of Alexander's team [ALE 77, ALE 00, ALE 04, ALE 05] enabled them to formulate the laws of geometric and energetic similarity for a large number of living animals. Figure 1.1 depicts, for example, the results obtained from the measurements of the length and diameter of femurs and tibias. For the femurs of primates, for example, these laws of similarity can be expressed in the following formula:

$$l = 100\,m^{0.34} \tag{1.1}$$

$$d = 6\,m^{0.39} \tag{1.2}$$

where l and d represent the length and diameter of the femur (mm), respectively, and m the mass of the body (kg). It has been convened that the laws of similarity can be defined by normalizing the sizes in question. The preceding relations therefore become:

$$l^{*} = (m^{*})^{0.34} \tag{1.3}$$

$$d^{*} = (m^{*})^{0.39} \tag{1.4}$$

where l^{*}, d^{*} and m^{*} are the normalized length, diameter and mass, respectively. For the same species, studies have shown that they are satisfactory for a large number of bones in the skeleton.

In the same way, the respective durations of the single and double support phases and the relations giving the length and frequency of steps during walking or running have been established by researchers. Figure 1.2 show the measured values for the lengths of steps for different living bipeds The dotted vertical lines on the right-hand side of Figure 1.2 indicate the transition zone between walking and running for the bipedal animals under consideration [HIL 67].

We notice that this zone is small which implies that all bipeds modify their gaits for the same relative speed (as defined by Froude's number) even when their size and morphology are different.

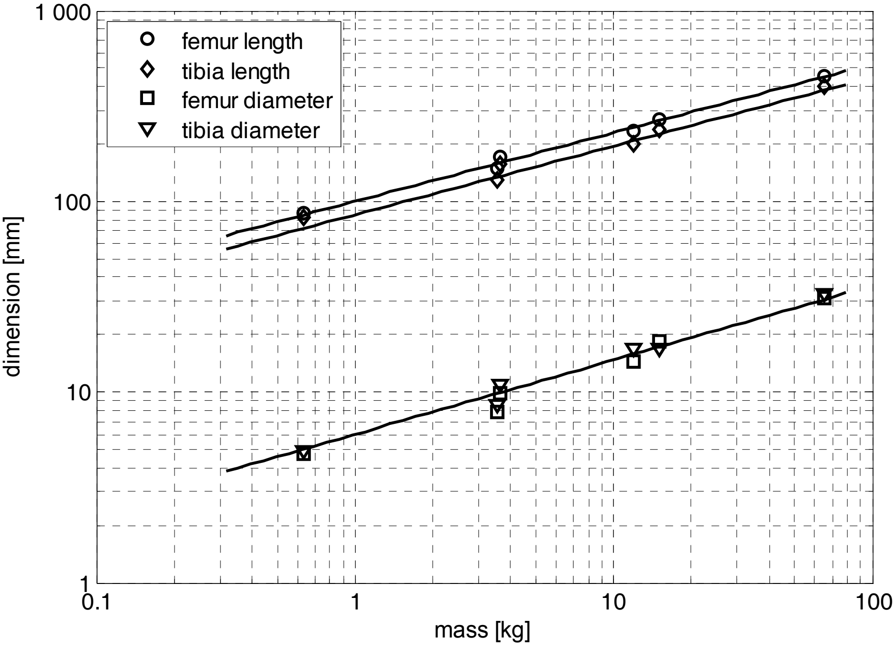
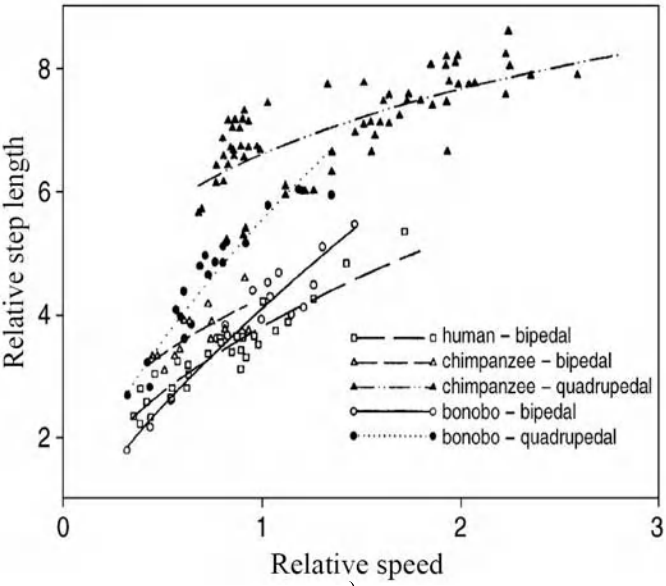
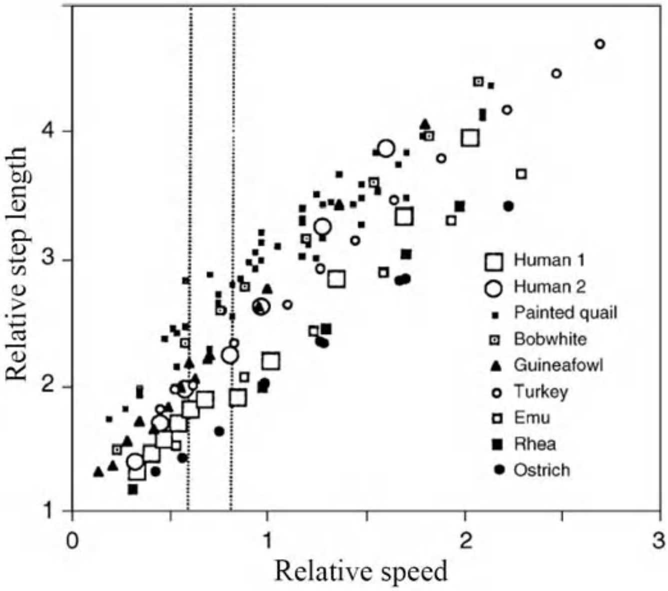


Figure 1.1. *The law of similarity which defines the length and diameter of the femurs and tibias of primates according to Alexander et al. [ALE 79]*



a)



b)

Figure 1.2. *Relative length of walking and running steps for humans and different bipedal animals dependent on the relative speed of progression (according to [ALE 04]). The relative speed is the ratio of the forward speed divided by* $\sqrt{gl}$ *(where g is acceleration due to gravity and l is distance from the hip to ground in the upright position)*

Energy consumption is a very important criterion in the design and study of bipedal robots. The study of the measurements of the energetic consumption of living things is also of evident interest. It is not easy to take measurements of consumed energy per living thing unit of time during walking or running or during any other physical activity. The measurement of the consumption of oxygen per unit of time seems to be the most representative of the total amount of consumption linked to physical activity. The studies of [MAN 80, THY 01] have provided a lot of information on this subject.

Simulation models have also been established from physiological data and have enabled us to plot the energy consumed per human during walking for different speeds and per unit of distance traveled.

Figure 1.3 shows the results obtained by Sellers *et al.* [SEL 04] which measure the energy consumption of a walker during 1 hour and traveling over a given distance (see graph legend) depending on the speed of walking (the tested subject remains immobile when he has traveled the given distance in less than an hour).

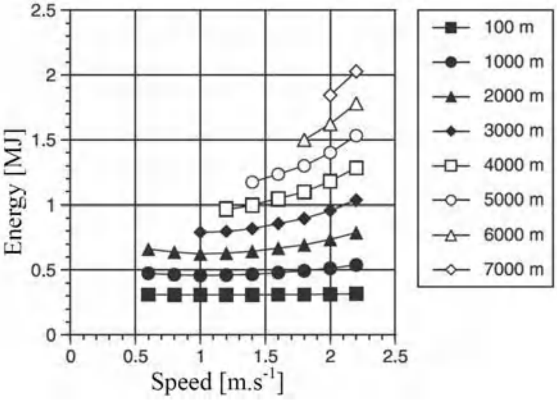


Figure 1.3. *Energy consumed per human during walking depending on the average speed of progression and the distance traveled (according to [SEL 04])*

Data recently published by Marden and Bejan [BEJ 06, MAR 05] show that the actuators used in nature and electromechanical or thermal actuators follow identical laws of similarity.

Marden has identified two family groups of actuator: the first produces linear movements (myosin, DNA polymerase muscle, linear electric motor) and develops a maximum force given by relation [1.5], whereas the second family group corresponds to rotation or beat movements [SCH 04] (insect or bird flight, swimming fish, electric or thermal rotating motors) which deliver a force given by relation [1.6]:

$$F_{\max} = 891 m^{0.67} \qquad [1.5]$$

$$F_{\max} = 55 m \qquad [1.6]$$

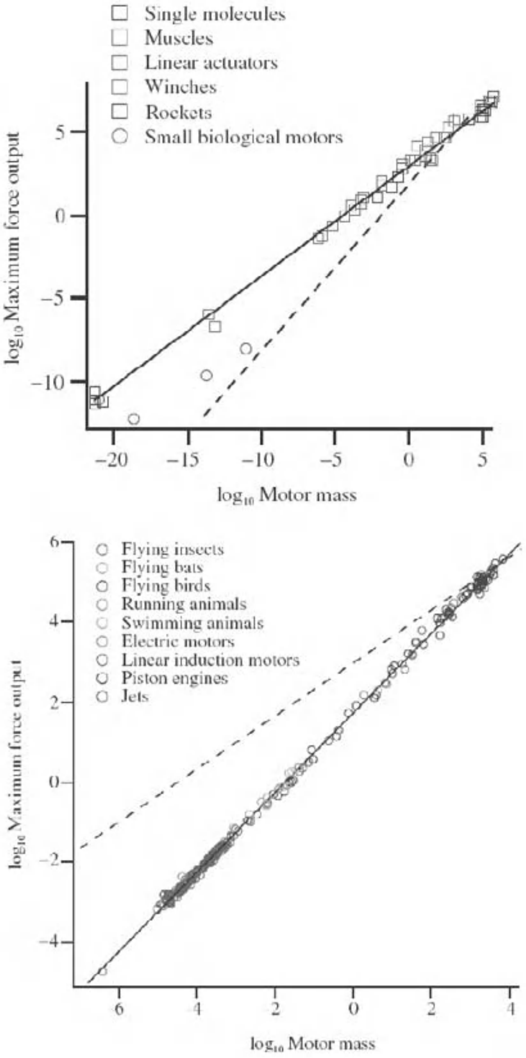


Figure 1.4. *Mass-force relation for different types of actuator (according to [MAR 05])*

Figure 1.4 shows the force produced by an actuator depending on its mass for a set of very different actuators with respect to the origin of the energy that they convert. The corpus of the different types of actuator can therefore be described by the curves in Figure 1.4. Relation [1.5] is represented by the continuous lined curve in the top graph, and the dotted lined curve in the bottom graph. Relation [1.6] is represented by the continuous lined curve in the bottom graph, and the dotted line in the top graph.

In short, biologists have put to the forefront the similarities between the locomotive behavior of animals regardless of their sizes and weights. Following measurements taken from animals of similar anatomic types but of differing sizes, Hill [HIL 50] arrived at the conclusion that for animals of similar morphology, speed is independent of sizes to within a scale factor. In this way, an animal makes movements of amplitude which are proportional to its size and at a frequency which is inversely proportional to this same size. During the study of the effects of scale on the structural adaptation of animals, three main types of similarity were brought to light.

The first is of geometric similarity, where two structures are geometrically similar if one can be obtained from the other by a uniform change in scale factor.

The second is the elastic similarity which allows deformations of the spinal cord without risking lesions [MCM 75].

The third is the dynamic similarity which includes morphological variations of animals of different sizes, the evolution of the movements and their delivered efforts. According to Alexander [ALE 83, ALE 84], two movements are dynamically similar if one can become the other by the uniform change of one or more of the three scale factors: length, time and force.

It has been demonstrated that when the forces of gravity and inertia are preponderate, two movements are dynamically similar only if they have the same Froude number:

$$F = \frac{v^2}{gl} \qquad [1.7]$$

where g is the acceleration of gravity, v is the average horizontal speed and l is the height of the hip from the ground in the upright position. Man moves from walking to running at a Froude number of 0.6 [BRU 98].

1.2.2. *Skeletal structure and musculature*

Bipedia has two main gaits: walking and running. When walking, there is always one of the two locomotive limbs in contact with the ground.

When running, a grounded monopodal impulse propels the body up and forwards in the form of a leap, followed by a new grounding with a shock to the other locomotive limb.

The kinetic energy of this ballistic phase is partially recovered at renewal support, thanks to the elasticity of the articulation, muscles and tendons.

The energy necessary for the leap is partially recovered when new contact is made with the ground. There is a left to right alternate weight transfer between the lower limbs.

Monkeys only use bipedia occasionally. They are not actual quadrupeds either because their upper and lower limbs end in hands with opposable thumbs, which are adapted for brachiation. They walk in this way on four hands which, in addition, have no pedal arches.

Bears also use bipedia very occasionally. Nevertheless, they are real plantigrade quadrupeds; they do not have opposable thumbs on any of their legs and when walking, their pedal arches are fully in contact with the ground.

The locomotive system of kangaroos is made up of lower pelvic members and a tail.

Birds, whose origins can be traced back to the theropod dinosaurs of the Jurassic period [DER 70], use a terrestrial system of locomotion where only the pelvic limbs remain, dissociated from the caudal region from their distant Jurassic ancestors.

The feet of birds are characterized by a tri-segmented Z structure: the femur, the tibiotarsus and the tarsometatarsus [MED 06]. The spinal cord of birds is fixed from the pelvis to the nape. Its central skeleton can therefore be considered as an undeformable solid.

The human spinal cord has a great number of individual mobilities. The trunk is also articulated in this way. Its movements have an influence on its locomotion. The spinal cord has a system of muscular tensors which take into account the constraints due to the alternating weight transfers from the lower right to the left limb during walking or running.

The human locomotive system stores and gives back energy (see section 1.2.2) due to the elasticity of the foot's arch, its muscles, its ankles and its spinal discs.

Nordez's [NOR 06] work on this matter gives a very detailed characterization of the passive stretch of the musco-articular complex. It was noticed that a static stretch brings about a mainly transitory increase in the length of muscles, whereas the dissipative properties and stiffness are only modified after cyclic stretches.

Nevertheless, to maintain an adequate level of mechanical energy for locomotion, the muscles transform chemical energy into mechanical energy, resulting in a global energetic demand.

To carry out the mechanical modeling of anthropomorphic structures, some authors have suggested models for the distribution of mass, the choice of segmented joint-links (and the number of segments) and their geometry [HAN 64].

To illustrate this, Figure 1.5 shows the skeletons of two bipedal animals (a bird and iguanodon) and a human in the upright position.

a) b) c)

Figure 1.5. *Skeletons of three bipeds: (a) a bird; (b) an iguanodon; (c) a human*

1.3. Human walking

1.3.1. *Architecture*

The architecture of a human's lower limbs is very complex (see Figure 1.6). Its bone structure regroups 44 bones, of which the femur, tibia and fibula are the main bones. Apart from the knee-cap, the remaining bones make up the foot, which can be considered as a deformable composite corpus.

Each member therefore has an ensemble of three main corpuses (thigh, leg and foot) linked together by articulations which have many degrees of mobility.

In this way, the hip articulation has 3 revolutionary degrees of mobility. The articulations of the knees and the ankles each have two DoF.

The musculature of a human's lower limbs is made up of 46 skeletal muscles. The muscles which intervene in the propulsion movement are longer muscles. In this way, we notice that many muscles intervene simultaneously to assist in the motion of an articulation. The muscles make an effort of traction and they always work in conjunctive pairs with another opposite muscle.

We can also separate muscles into those which only act on a single articulation (e.g. the iliacus muscle on the hip) and others, which act on separate body-links, which are separated by two articulations (e.g. the rectus femoris muscle).

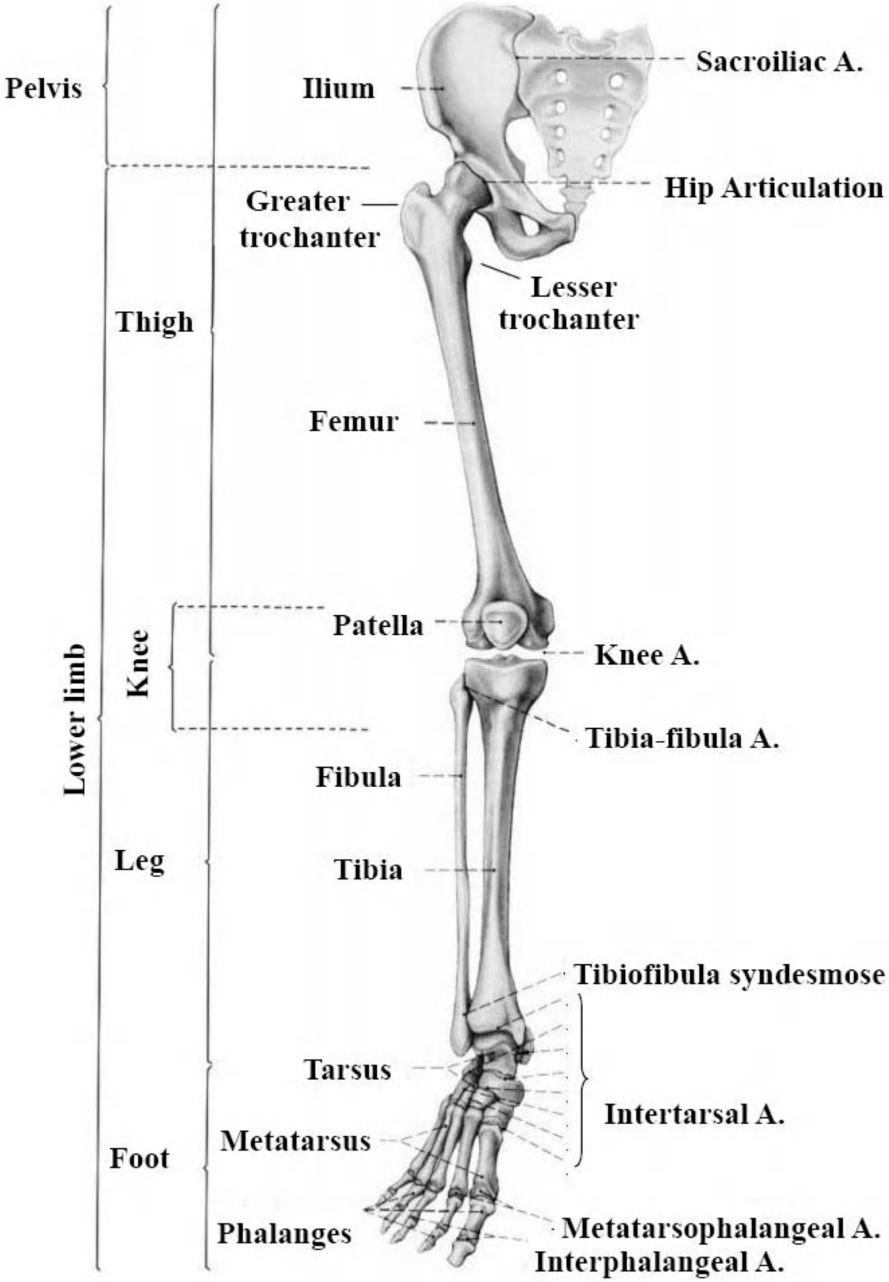


Figure 1.6a. *Structure of human lower limbs: skeleton of the right leg*

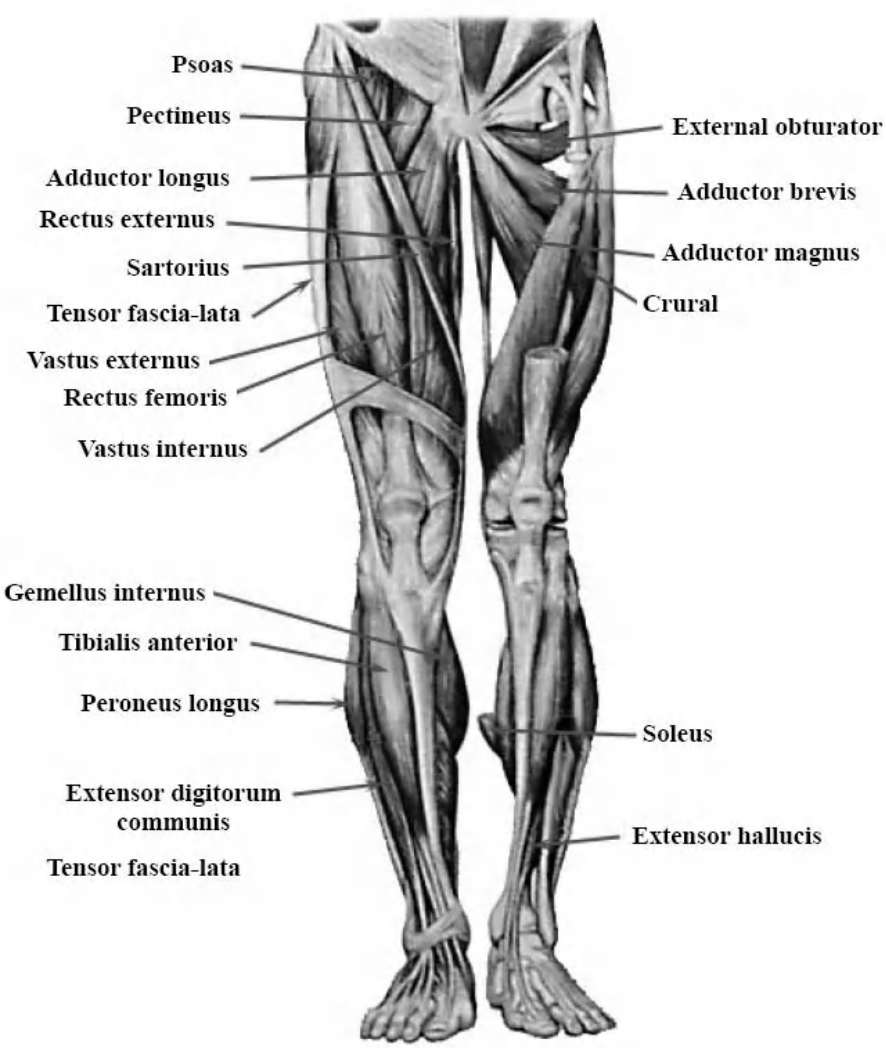


Figure 1.6b. *Structure of human lower limbs: ventral frontal view of the muscular groups*

1.3.2. *Walking and running trajectory data*

In a healthy subject, locomotion can be reduced to a cycle [GAG 90, LAA 92, NIL 89], where the articulate sequence is repeated as long as the speed is constant.

Walking, for example, is a succession of grounding phases and balance. It has been convened that the walking cycle starts when contact is made with the right heel, followed by two steps, left then right, where the walker maintains at least one grounding. By dividing up this cycle into percentages of its duration [BEA 03, VAU 84], the contact of the right heel with the ground is considered as instantaneous (0% of the duration of the cycle) (Figure 1.7).

Both feet are grounded for 0–15% of the cycle. This is a phase of double support which corresponds to the grounding reception of the right leg, and the propulsion of the left leg. In a progressive way, the left foot leaves the ground, until the big toe has left the ground. For 15–50% of the cycle, only the right foot is grounded in a monopodal phase. The left leg is in a balancing phase. When the left heel impacts with the ground and the left foot grounds, there is a second phase of double support for 50–65% of the cycle. This phase is completed by the big toe of the right foot leaving the ground. For 65–100% of the cycle, we are in the monopodal phase on the left foot. The right leg is in the balancing phase. The cycle terminates by a new grounding of the right heel.

Human walking is characterized by a phase of double support which disappears during speeds faster than 2.1 m s^{-1}. This disappearance corresponds to the theoretical transition of walking with an instantaneous double support to running which represents 50% of the cycle (see Figure 1.7).

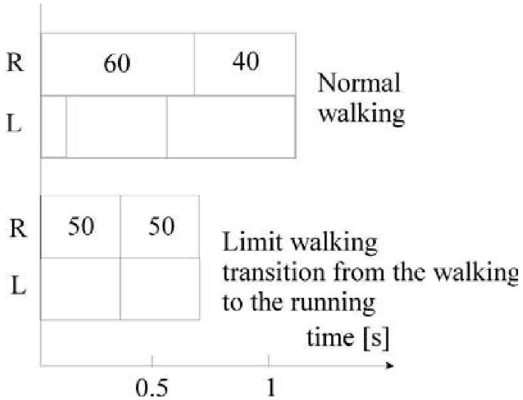


Figure 1.7. *Grounding phases (gray areas) expressed in percentages of the walking cycle duration*

According to various studies [AND 77, LAR 80], distance *D* which is covered during a cycle increases linearly with speed, until it reaches a maximum. Van Emmerik and Wagenaar [VAN 96] have shown a variation of 0.6–1.4 m for speeds