Vysoká škola finanční a správní, a.s.

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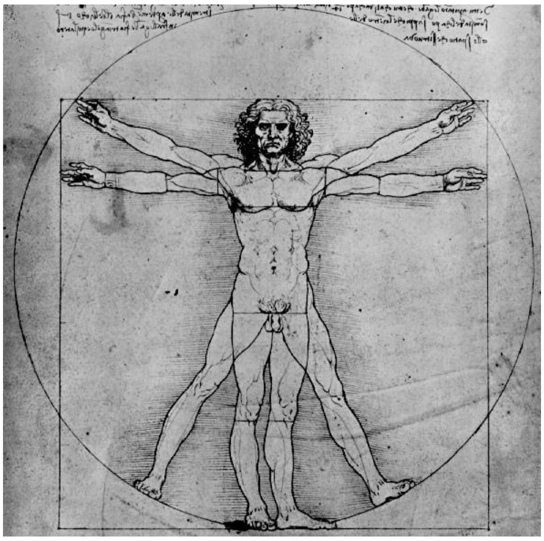
# FORENSIC BIOMECHANICS
## Criminalistic and Forensic Applications



PRAGUE 2018

Suggested citation:
PORADA, V. and J. STRAUS. *FORENSIC BIOMECHANICS. Criminalistic and Forensic Applications.* Prague: VŠFS, SCIENCEpress, 2018, ISBN 978-80-7408-168-2.

# FORENSIC BIOMECHANICS
## Criminalistic and Forensic Applications

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The book has been supported by the Institutional support for long-term strategic development of the research organization University of Finance and Administration. It is the outcome of the research assignment of the Internal Grant Agency of VŠFS No. 7429/2017/07 entitled "New Possibilities of Investigating Forensic Footprints with Biomechanical Content and Interpretation of Conclusions of Expert Investigations" (researchers – J. Straus and V. Porada).

Publisher Vysoká škola finanční a správní, a.s. (University of Finance and Administration)
Edition SCIENCEpress
Estonská 500, 101 00 Praha 10
www.vsfs.cz

Editor doc. Ing. Milan Kašík, CSc.
Publishing Editor Mgr. Petr Mach
Pages 235
First edition, Prague, 2018
Print Česká digitální tiskárna s.r.o., Hviezdoslavova 614/16, 400 03 Ústí nad Labem

This publication has not undergone language editing, for the content ans linguistic aspects of the text take responsibility the authors.

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**ISBN 978-80-7408-168-2**

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# Contents

# Introduction

Biomechanics deals with application of mechanics principles to biology, medicine, physical education and sport, criminalistics, etc. This simplified definition, however, cannot be understood one-sidedly. Scientific knowledge of biology enhances our understanding of inanimate nature behavior and the problems of mechanics itself are currently complex and complicated. Mechanics studies the motion and mutual interaction of all kinds of surroundings spanning a range of study from elementary particles of matter to problems encountered in space research; a system which, applied together with cybernetics, has helped us to comprehend processes that occur in both inanimate and animate matter.

This publication issues from the scientific need and social benefits of biomechanics development as general on the one hand and development of special criminalistics and forensic application on the other hand. Consequently there are included these demanded attributes into because they less or more closely but yet naturally relate to the systems of interactions between a human being (a perpetrator) and surroundings. Above all there are the problems of tissues, organs and organs structures (mechanical characteristics especially) that were worked out by Valenta (1985, 1992, 1993, 1997, 1998, 2000, 2002), Komárek (1985, 1992, 1993) and the problems of human being locomotion apparatus aimed at essential issues of mechanical structure and behavior of human being locomotion apparatus as a whole developed especially by Karas (1978, 1985, 1992, 1993), Otáhal (1985, 1992, 1993). The other part of the publication is aimed at application that uses knowledge of both basic and applied biomechanics research in trasology and hand-writing (criminalistics biomechanics) and also in the course of studying extreme dynamic loading and falling of persons (forensic biomechanics) worked by Porada (1981, 1985, 1987, 1992, 1993, 2001, 2002, 2003), Straus (1999, 2000, 2001, 2002, 2003), Liška (1992, 1993).

Biomechanics application in criminalistics started to be developed in the former ČSFR in 1974, at VŠ SNB in Prague, at the department of criminalistics and theory on public security activity, consequently at FMV Institute of Education and partly at VB Criminalistics Institute in Prague. When Akadémia Policajného zboru SR in Bratislava was established the biomechanics application research continued there at the department of criminalistics and forensic disciplines and in the end at Policejní akademie ČR in Prague at the department of criminalistics and scientific research department.

The publication is intended not only to contribute to further development of criminalistics and forensic biomechanics applications in the Czech and Slovak Republics but also to help scientific workers in basic biomechanics research and doktorands of technical and medical sciences aimed at principal issues of mechanical structure and human being locomotion apparatus behavior and its interaction with surroundings.

This publication is considered to become the fundamentals of constituting and developing criminalistics, forensic, forensic medical and forensic engineering application in biomechanics in the course of carrying out an intended research and a project of the international scientific workers team comprised of members of the criminalistics department of Police Academy ČR in Prague (prof. Straus, prof. Porada), department of criminalistics and forensic disciplines of Akadémie Policajného zboru SR in Bratislava (prof. Porada), scientific workers of Forensic Engineering Institute VUT at Brno (prof. Bradáč) and Forensic Engineering Institute ŽU at Žilina (prof. Kasanický) and Vysoká škola Karlovy Vary (prof. Porada, prof. Straus).

This publication is a close follow-up to the publication by Valenta, J. et al. (among others, V. Porada) Biomechanics. Praha: Academia 1985, Valenta, J. et al. (among others, V. Porada) Biomechanics, Clinical Aspects of Biomedicine, 2. Amsterdam-London – New York – Tokyo: Elsevier, 1993, Porada, V., Straus, J. Criminalistic and forensic Biomechanics. Praha: Police History, 2001; Valenta, J., Porada, V., Straus, J.: Biomechanics (Criminalistic and Forensic Application), Prague: Police History, 2002, Valenta, J., Porada, V., Straus, J.: Biomechanics (Aspects of General and Forensic Biomechanics), Prague: Police History, 2003, Valenta, J., Porada, V., Straus, J. Biomechanics. Aspects of Generaland Forensic Biomechanics (Criminalistic and Forensic Application. Prague: Police History, 2004.

The monograph "Forensic Biomechanics, Criminalistic and Forensic Applications of Biomechanics" was developed by standard, identifiable and scientifically recognized methodology of forensic science development. The book deals with a well-defined forensic biomechanics problems. The methodological basis is based on theoretical research so far and the scientific conclusions are oriented towards practical applications in criminal practice.

The monograph is the outcome of the research assignment of the Internal Grant Agency of VŠFS No. 7429/2017/07 entitled "New Possibilities of Investigating Forensic Footprints with Biomechanical Content and Interpretation of Conclusions of Expert Investigations" (a responsible researcher – J. Straus and a resercher – V. Porada).

The authors of the book would like to thank for their invaluable advice to all of reviewers: prof. Ing. Roman Rak, Ph.D. and doc. Ing. Jaroslav Suchánek, CSc.

We are also obliged to thank everyone who helped us to publish the publication, especially the PhDr. Katarína Greňová, Ph.D. student at FF UPJŠ in Košice, Hana Víchová from VŠFS in Prague (for the transcription of a difficult and technically complex text), student Tobiáš Greňa (for help with English translations and creation of some pictures and charts), but especially Mgr. Petr Mach, the publishing editor of the publication, for an unusual temporal affection and very valuable help without which this monograph could not come.

The authors

# 1 Genesis and prospects of forensic biomechanics

## Introduction

In recent five or ten years in a criminalistic scientific community there has been a clearly evident scientific discussion on a criminalistics science theory, criminalistics system, matter of criminalistics and a relation of criminalistics science to other scientific fields, primarily to forensic sciences with whom criminalistics is closely connected. Due to proceeding scientific knowledge and research of these scientific fields in past times somewhat related to criminalistics this relation has been deepen step by step.

Criminalistics is a fundamental police discipline and if it makes some sense nowadays then its theoretical, systemic, mathematical and police detail must be stressed. After establishing a police science criminalistics hardly loses its independent position within the science system, quite the contrary it will be developed in the police science framework and will have an impact on the police practice.

Criminalistics is explicitly comprehended as an independent scientific field having its institutional base in a series of criminalistics research and expertise workplaces all over the world. Even though criminalistics includes and uses the elements of technical and natural sciences due to its aims it belongs to the social sciences. There is the closest connection between the criminalistics and legal sciences. (Legal sciences are sciences dealing with the law.) Although some criminalists regard criminalistics as a legal science, Czech and Slovak criminalists do not consider criminalistics to be part or branch of a legal science. Anyway criminalistics does not investigate connections of law or legal relations.

Criminalistics is closely connected with criminology. Both of these two scientific disciplines study the indentical objects but connections of objective world investigated by criminology diametrically differ. Criminalistics is also closely connected with a substantive law, law of procedure and as well with part of an administrative law – a security law. However these legal branches only create a legal framework for criminalistics science and also for criminalistics practice.

Even criminalistics has a close relation to a number of natural and technical sciences so the criminalistics science borrowed knowledge from mathematics, physics, chemistry, biology, anthropology, mechanics, and from other scientific disciplines. Criminalistics borrows knowledge from these sciences with the aim to adapt them in a qualitative way to criminalistics methods unravelling events relevant to criminalistics.

Criminalistics science also borrows a portion of other sciences knowledge in an unchanged form and uses them. It deals above all with forensic disciplines such as forensic medicine, forensic psychiatry, forensic psychology, forensic engineering and lately also forensic biomechanics. These disciplines have been constituted on the basis of the expert research to meet the demands of the investigation and they are relatively independent on original scientific foundations. Forensic disciplines began successively developing research activities of their own on knowledge basis not only through their parent fields but also through the generalization of acquired experience from expert activities. So in this way they established a very close relation with criminalistics. Some opinions emerged making possible to comprehend forensic sciences as part of the criminalistics science in a broader sense but this attitude has not been accepted by our criminalistics community yet. The forensic disciplines are mostly objected to draw their fundamental part of knowledge from their parent disciplines. However it is indisputable that contacts between criminalistics and forensic sciences are exceptionally close. They enrich each other and to determine the line between them is impossible in essence.

In present times, criminalistics is in regards to contents and forms of research an independent and widely interdisciplinary scientific field. Criminalistics uses specific methods and knowledge from other fields and applies these methods to its own subject of examination (patterns of formation, accumulating and using of traces and forensic evidence), and creates combination of information in the interest of successful discovering, investigating and preventing criminal activity. Scientific fields of which chosen information are used in a creative manner, involve mainly physical mathematical and technical fields, biology, medicine, psychology, psychiatry, management, pedagogy and others. Also important is using of knowledge from special disciplines, such as bionics, biochemistry, cybernetics, forensic engineering or a new, very progressive branch of forensic biomechanics.

Criminalistics also uses parts of knowledge from other sciences in their unaltered form. It concerns mostly **forensic sciences**, such as forensic medicine, forensic psychiatry, forensic psychology, forensic engineering and recently also forensic biomechanics (Straus 1999). Forensic sciences are generally restricted to sciences which are applied to investigation and substantiation regarding criminal and civil trials in front of state administrative bodies. This concerns procedures leading to revealing identity, authenticity of documents etc.

These disciplines are constituted based on an expert examination. The investigation requires them to be relatively independent from their original scientific foundations. Forensic disciplines began to develop their own research activity based not only on the information drawn from their own native scientific fields, but also on the generalization of the acquired observations from the examinations. This means that forensic disciplines are very closely connected to criminalistics. Some opinions suggest that it could be possible to perceive forensic disciplines as part of the crime science, but this approach is not yet accepted by our criminalistics community. It is often objected that forensic disciplines draw most of their expertise from their native scientific disciplines. However, we cannot deny the fact that the connection between criminalistics and the forensic disciplines is extremely tight, reciprocally enriching and it is basically impossible to draw the line between the two.

The term forensic science in western literature is quoted variously, for example the **American Academy of Forensic Sciences** (AAFS) defines it: *"The forensic science is an application of the scientific principles and technological procedures for the purpose of impartialness in studying and solving criminal and civil inquiries"* (2015). In this definition, the AAFS considers criminalistics as one of the forensic sciences.

In the last twenty years, many terminological and theoretical opinions arise, questioning the use of the term "forensic". Experts ask what is **the relationship between**

**criminalistics and forensic sciences from the point of view of present criminalistics theory**. In the last two decades, forensic sciences are often discussed in our criminalistics literature. Before the year 1989, forensic sciences were only discussed regarding the integration of collateral scientific fields into the criminal examination. When the borders opened and the import of western literature into our culture began, the terminology of western countries along with terms such as “Forensic science” or “Forensische Wissenchaften” started being used.

It can be stated, that the term “forensic” in our criminalistics literature was developed from the earlier used term “criminalistic-technical”. However, the criminalistic-tactical methods are not viewed as forensic. The terms such as forensic ballistics, forensic anthropology, forensic biology, but also forensic psychology, psychiatry etc. are commonly used. On the other side, we do not use the terms forensic interrogation, forensic experiment, forensic recognition and so on. From this we can conclude that forensic sciences can be replaced in our conditions with the term “criminalistic-technical”.

From our point of view, criminalistics is a wider scientific discipline that also incorporates forensic sciences. Criminalistics involves not only criminalistic-technical methods, but also criminalistic-tactical methods, individual methodologies of investigating crimes, and theoretical questions of criminalistics.

We can notice two major views of criminalistics. In the countries which use Anglo-Saxon law, especially in the USA and the Great Britain, criminalistics is labeled with the term *forensic science*. Understanding of criminalistics has its ground mainly in biological and technical examination and the technical and criminalistic examination of traces is greatly accentuated.

In the countries of continental law, the term “criminalistics” is more frequently used. This term involves not only the field of technical examination, but also criminalistic tactics and methodology. Some countries emphasize the technical side (France), while other prefer the scientific basis (USA). Although, the term “criminalistics” is nowadays used more and more often and the approach and terminology are beginning to uniformalize.

Criminalistic science is always going to develop in such way and tempo that is set by the theoretical base. I advocate the opinion that this development is not only set by the theoretical base, but also by the criminalists-theoreticians themselves. That’s why it is necessary to not only develop the applied, imminent research, but also spend intensive time and theoretical research on major criminalistic problems and categories.

## 1.1 What are the current forensic sciences like?

The group of scientific fields making the solving and unravelling of crimes possible is known for their different terms. Criminalistics is the first one and forensic science appears to be the second one. The term criminalistics is simply derived from an English word crime = zločin. The origin of term forensic is in Latin word – forum which means market. So that’s why the law in a Roman society was executed publicly at markets. The word forensic is broadly accepted as the name of anything connected with the law execution.

Due to the progress of scientific knowledge forensic sciences have been expanded and at present it is possible (in ours opinion) to specify them like that:

1. Forensic medicine.
2. Forensic psychiatry, psychology….
3. Forensic sexology.
4. Forensic engineering.
5. Forensic biomechanics.
6. Forensic biology, antropology…
7. Etc.

From time to time there are some efforts in a professional literature to include only marginally into forensic sciences also forensic entomology and forensic anthropology (the term forensic anthropology is very frequent in Slovak professional literature). Even the term - criminalistic molecularly genetic expert opinion has in scientific circles its equivalent – forensic genetics. These applications have not been profiled into independent scientific disciplines and so they cannot be comprehended for the time being as independent forensic scientific disciplines.

Forensic sciences significantly influence criminalistics science development and contribute to objectification of decoding criminalistic relevant information coming from criminalistic traces. Forensic sciences professional range is quite broad.

## 1.2 Biomechanics and its current structure

Biomechanics is defined as a field which contributes to the solution of those biological and medical problems, including the sub-problems of a mechanical character, the so-called "biomechanical problems". They use the knowledge, approaches, methods and theories of mechanics. Biomechanical problems are solved on biomechanical objects, which can be of a different nature. These may be elements of the flora or fauna in Biomechanics it may be a technical object, in different interactions with the human organism (implant fixator), or is itself the human organism as a whole or its unseparated (in vivo), respectively. separate part (in vitro).

Biomechanics is thus defined as a discipline that exploits everything from mechanics to solving problems in the field of bioobor, especially in medicine and biology (Janíček 2008).

Biomechanics is defined as interdisciplinary science, focusing primarily on the mechanical structure and mechanical behavior of living systems and their interactions with the environment (Karas 1978).

Biomechanics is at the beginning of its development, but has already achieved many successes. Its goals are limited so far, because it soon became clear that the description of isolated phenomena did not provide usable results. That is why we are gradually turning to modeling of complex systems today, at the cost of difficulties in mathematical description and experimental techniques. We have shown that the new quality of the system was created by the transfer of information and its processing. However, this is connected with the integrity of the whole system and its reaction to the environment. The current methodology of studies is still largely devoted to efforts to isolate parts of the whole and to describe their connection by simpler boundary conditions, as is the case in the classical mechanics of the continuum. The current goal is to obtain generally valid knowledge as simple as possible and in a sufficiently precise manner (Valenta et al., 1985).

More mathematical models need to be used to describe more complex knowledge. The mathematical model describes reality only approximately, but without it it is not yet possible to work with the mechanics.

The first step is to find the geometric parameters of the tissues, organs, organ structures and substructures of these objects we are studying, and the choice of their appropriate models (plate, beam, membrane, fiber etc.).

The second step is to find out the material properties and again to choose their corresponding models, ie constitutive or material equations. For biomechanics, it is characteristic that this step is very difficult. It follows from the fact that the material properties of living tissues are complex (neline arita, history dependence, great deformation) and, moreover, we can study the tissues, we have to remove them from the body (mostly post mortem), and then we examine the properties that are already partially different from in vivo conditions. However, finding this fact is not a challenge to pessimism, we need only be aware that we are working with less precision than classical mechanics, and therefore we need to place greater emphasis on constant verification and comparison of the results we get from different approaches.

The third step is the mathematical processing of the given task: Based on the general laws of mechanics, information on the geometry of the external and internal structure, and finally on the basis of material equations we derive the initial equations corresponding to the given problem and solve them for the respective marginal or initial conditions.

The fourth step is to verify the results by observing and measuring on an object, preferably in in vivo conditions, and correcting the initial hypotheses and parameters.

The fifth step is to use in diagnostics, therapy, prevention, or application in technical constructions. This whole journey is difficult and so often uncompromising. History of science, however, teaches us that partial knowledge has often been used with excellent results, and much later, the issues have been thoroughly elucidated and understood (Valenta et al. 1985).

The equations of mechanics developed for the action of bodies must naturally apply to living organisms, but they are not sufficient. The main subject of biomechanics is the study of processes in complex living systems and the axioms of classical mechanics are the basis from which the laws of thermodynamics of open systems, microbiology, etc. have to be based and are gradually being supplemented. See, for example, Janíček, Ondráček, Porada 1996, Janíček, Porada 1996).

Biomechanics can be broken down by these criteria (Janíček 2008, pp. 10−19):

1) **Depending on the type of bio-object** on which the biomechanical problem is addressed, there are::

- **Biomechanics of humans** - it is the largest and most elaborate field of biomechanics, dealing with a wide range of biomechanical problems. Its origins date back to the time of Aristotle (emphasizing the necessity of interconnecting physics with living objects), Demokritus (explained in a coherent way the properties of living and inanimate matter on the basis of atomism) and Hippocrates (a treatise on the renewal of bone tissue). Leonardo da Vinci first described the mechanics of human body movement and bird flight mechanics.

- **Biomechanics of animals** - deals with many similar problems like human biomechanics.
- **Plant biomechanics** - deals with, for example, stiffening and strength problems of stalks of plants, flow of nutrients through individual parts of plants, transmission of electrical signals during photosynthesis.

2) **By the mechanics sector,** which is used to solve a biomechanical problem. There are:

- **Biotermomechanics** - deals with the problems of conducting, sharing and convection of heat in bioobjects.
- **Biohydromechanics** - deals with hydromechanical and hydrodynamic problems of biocapalins (in lice trees, in human blood, lymphs, urine).
- **Bioaerodynamics** - deals with the flow of gases (eg air flow through the nose, around the vocal cords, the larynx and the lungs).
- **Solid Phase Biomechanics** - deals with the movement of bodies, their deformations and violations of cohesion.

3) **Depending on the type of modeling it uses to solve the problems of human biomechanics:**

- **Experimental biomechanics** - when the problem is solved, the experiment has the current preference - calculations only have a secondary role; they are mainly used in the processing of measurement results, also as part of measurement planning.
- **Computational biomechanics** - the current modeling problem is the preference for solving problems. Its use is conditional on the existence of theory in mathematical expression, its solvability and feasibility on the computing means, and there must also be input data into the algorithm of the respective direct or indirect task. At present, numerical methods are used in the solution of biomechanical problems for clinical practice, especially in the form of the finite element method.

4) **Depending on the target behavior of biomechanics:**

- **Cognitive biomechanics** - it has the character of a purposeful, systematic and objectified knowledge of bio-organisms from a certain point of view using mechanics. Above all, it is about knowing the properties and behavior of the elements and their linkages in the bioequence, the properties and behavior of the bioobject as a whole and its links with the environment. These include, for example, research into the mechanical properties of tissues, their behavior under load, limit state of tissues, properties research and flow of biotekutins, kinematics and dynamics of the musculoskeletal system,

- **Clinical Biomechanics** - deals with the solution of specific clinical problems in bioobjects whose structure (elements, links) has become a pathological condition, and there is a high probability that by linking medical and engineering approaches, possibly using technical implant objects, the pathological condition can be completely or partially removed. Clinical biomechanics can be temporarily or permanently implanted into implantable.
- **Constructive biomechanics** - the aim is to use knowledge and method of mechanics in the design and implementation of technical objects with a certain target behavior, which serve to solve clinical problems. Technical objects may be of a diverse nature: from surgical and orthopedic devices through temporary or permanent implants to devices to maintain or restore physiological functions.
- **Criminalist biomechanics** - is a collection of criminological approaches and methods utilizing the knowledge of mechanics to obtain and disseminate information on the causes of the offense, the objects involved in its implementation and the characteristics of the perpetrator, all based on known information about the consequences and circumstances of the offense . It is a crime of human traces in a bi-directional "human-environment" interaction that contains information decodable using the knowledge of mechanics.
- **Sports Mechanics** - is a discipline using mechanics to solve problems related to human activities,
- **Interactive Biomechanics** - deals with the problems related to the environment-human interactions, as well as the prevention of the adverse effects of these interactions and the rehabilitation problems in the elimination of their consequences. On the periphery, there is also the issue of the inversely oriented interaction, ie "man - environment", which is the object of ecological engineering. According to the elements of the human body structure, which are concerned with clinical and cognitive biomechanics. At the highest level of the hierarchy of the human body, it is the biomechanics of the individual functional systems of the human body. There are biomechanics: musculoskeletal, cardiovascular (circulatory), respiratory, digestive, urinary, reproductive, dental biomechanics and biomechanics of sensory organs. Biomechanics of skeletal, cardio-vascular, dental and urinary and biomechanics of auditory organs can be broken down into implantable and implantable.

5) **The biomechanics of the musculoskeletal system** can be divided into the following elements:

- **Biomechanics of hip, knee, elbow, ankle joint**. Non-implantation hip joint biomechanics, for example, addresses these problems by examining deformation-stress states in bones and hip joints and in articular cartilage in their physiological and pathological states. Biomechanical assessment of various types of osteotomies in the reconstruction of pathologically developed hip geometry.

Influence of the shear size (covering of the hip joint hip) on the distribution of the contact pressure between the hip and the hip.

- **Implantation biomechanics of the hip joint**. Possibilities of partial and total endoprostheses in terms of deformation-stress states in the elements of the endoprosthesis and in the adjacent bones. The problem of interactions of the endoprostheses with the adjacent bones, ascertaining the causes of the occurrence of mechanical limit states in the elements of the endoprostheses and the adjacent bones. Influence of hip endoprosthesis geometry, acetabular material structure and mechanical interaction of cemented hip endoprostheses with thigh bone.
- **Biomechanics of the spine**. Determination of deformation-stress states in spine elements in various methods of spinal strain, computational and experimental verification of stiffness and strength properties of lumbar fixators.
- **Biomechanics of long and short bones**. Structural and shape optimization of intramedullary nails used in fractures of femurs and sliding screws used in fractures of the neck of this bone. Controlled osteotomy of long bones.
- **Biomechanics of muscles** - tearing and tearing of muscles, tendons and tendons, micro-biomechanics, sarcomers etc.

6) **Biomechanics of the cardiovascular system** can be decomposed into the following elements:

- Heart Biomechanics
- Biomechanics of blood vessels
- Biomechanics lived

7) **Biomechanics of the dental system** - these problems are solved, for example:

- Computational modeling of deformation-stress states in bonded dental bridges made of composite materials, including determination of deformation limit states,
- computational modeling of dental teeth insertion, computational modeling of the dental implant interaction with the lower jaw,
- computational modeling of deformation-stress states in the lower jaw from the force effect between the teeth at various points of the lower jaw.

8) **Biomechanics of hearing system** - solved problems are:

- modal and harmonic analysis of the external auditory canal,
- the influence of the frequency and the shape of the oscillation on the response of the drum,
- cochley computational modeling and basilar membrane responses to mechanical excitation from middle-sized bones,
- deformation-stress analysis of middle ear bones when transferring sound to the inner ear.

Using biomechanics in criminalistics is first of all dependent on the crime trace itself. Opportunities for biomechanics use in criminalistics are also depend on the fact if the trace contains any biomechanical contents that means some coded information on perpetrator musculoskeletal apparatus and his locomotive behaviour reflected in the trace (Janíček 2008, pp. 20–35).

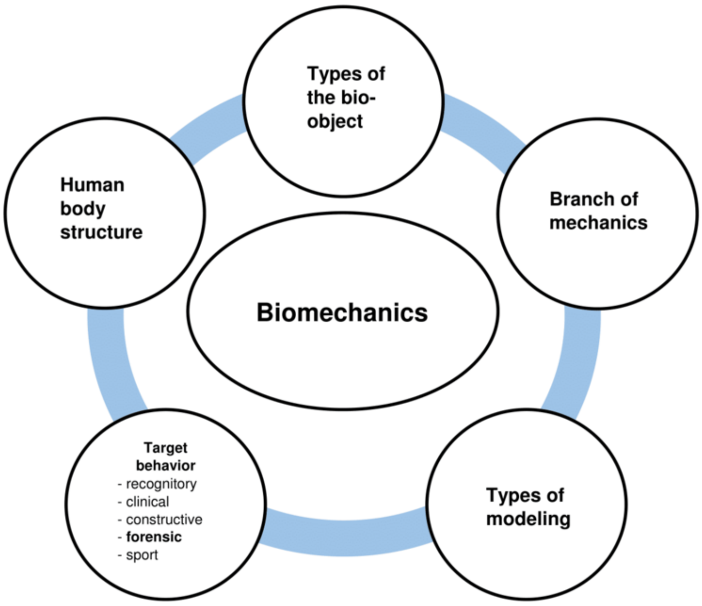

Fig. 1.1. Structure of biomechanics (Straus)

## 1.3 Forensic biomechanics genesis

Considering the first person identification methods really based on science were founded by A. Bertillon in 1879 (person identification according to 11 external marks that are accurately measurable) and such a classical criminalistic method of identification as dactyloscopy was introduced in this country in 1903, then forensic biomechanics has really been a very young field of a criminalistics technique.

**1. Period – the period of anticipating possible coherence – Marginal use within trasology – ”Prehistory of Biomechanics Applications”**

From the point of view of biomechanics applications dependence between the sole length and body height was studied at the very beginning. The outset of this theory can be already found in Bertillon’s work that said there are certain relationships among different (accurately measurable) proportions of a human body while many of them can be formulated by mathematical dependence. At the end of 19th century in A. Bertillon’s and H. de Parville’s works the dependence of a sole length and body height was being studied primarily.

On the basis of practical researches of their own (the extent has been unknown) both of them formulated given relations as a linear dependence and in their works the tables of reconstruction coefficients can be found as well.

The coefficient table published by Bertillon in Revue Scientifique in 1889 appears to be the oldest aid for body height calculation using the bare foot length. Later these reconstruction connections were dogmatically accepted very often without any correction and even with errors.

The other and in our opinion a more accurate method was published by H. de Parville in Revue Scientifique in 1899. He had reached relatively an accurate formula the applicability of which he checked up on more than 100 persons of various age and even on children.

$$d_n = \frac{8{,}6}{30}\left(\frac{v_T}{2} + 0{,}05\right)$$

From our present point of view it could be interesting that also in other works the connection is always included in a quite complicated form and has not been done in a more common form.

$$v_T = 6{,}98 \cdot d_n - 0{,}1$$

Later Feix (1965) reduced this connection much more by way of logical thinking that for variables in cm the absolute term valued at 0,1(cm) is inconsiderable and a coefficient of 6,98 can be rounded off to the whole number so then this connection has been simplified as follows:

$$v_T = 7 \cdot d_n$$

Both Bertillon and Parville mentioned a graphic representation of body height prediction by means of the foot length that could be compared and assessed. First of all it is obvious Bertillon's diagram has a non-linear shape however some irregularity in case of biological dependence is also possible but it is not too frequent. It can be some implication that the complex processed by Bertillon was not numerous enough. On the contrary Parville's dependence is linear and proves to be a straight line in a graph.

Comparing both of the authors another difference is the absolute value shift despite both measurements were carried out in a comparable time (1889 – 1899) being of use for one generation. Parville's results are higher in case of extreme figures of the foot length – almost more than 18,5 cm. (Even though I am aware of the basic anthropologic and motoric rule dealing with the fact differences can be found in absolute extremes best.

Hans Gross was another scientist studying the locomotion path for identification purposes. From present point of view it is admirable how much attention he paid to traces seeking, securing and investigating.

He felt as a necessary thing for criminalistic work to build up new scientific and above all natural scientific and technical ground. As a lawyer he had no professional knowledge in the sphere of exact or applied natural sciences. However he was a hardworking and far-sighted person also having some scientific intuition. He wrote a handbook titled "The magistrate's handbook" ("Handbuch für Untersuchungsrichter als System der Kriminalistik" - in the original) that was published in the town of Štýrský Hradec in 1892 and was intended to become the very first textbook of scientific criminalistics popularizing Gross's name worldwide. A number of recommendations and parts of this book are still valid. In Germany e.g. the latest edition of 1955 with a title "Handbuch der Kriminalistik" (Gross – Selig authorship) has maintained a larger part of the original edition.

It is very interesting the authors also made a remark about rudiments of trasological traces biomechanical investigations, they gave common formulas for body height calculations by means of mark length (by Parville), barefoot studies and gave elementary measurement means for locomotion path traces.

The early investigation of relationship between measurements of walk traces and a body height, further studying footprint identification value could be obviously found in the literature 110 years ago e.g. in the very first edition of the textbook by Hans Gross "Handbuch für Untersuchungsrichter als System der Kriminalistik" of 1892. Walk traces investigations related to a body height began emerging in criminalistics in the late 50s. In next 30 years biomechanics gained a greater and greater importance.

This period of the biomechanical applications outset and anticipating possible coherence can be hardly termed as biomechanical applications because the question was the logical use of some geometric regularities to assess the body height only. The authors did not use the terms as "biomechanical applications" or "biomechanics use" etc. Personally, I would refer to this period as "Prehistory of forensic biomechanics".

### 2. Period – Biomechanics applications in criminalistics

This period was a period of theoretical studies aimed primarily at biomechanical contents of trasological traces.

In the early 70s a noticeable study was published that continued ideas of Bertillone and Parville and it investigated a relationship between a body height and sole length. The measurement was done by means of 116 men complex and in a standard way needed figures were gained while through statistical processing relations for body height calculations using sole length and width or footprint length and width or also footwearing print length and width were determined. E.g. body height prediction could be:

$$v_T = 2{,}5 \cdot d_n + 4{,}5 \cdot s_n + 64$$

In 70s the research characterized as "Biomechanics applications in criminalistics" in particular thanks to Viktor Porada and Vladimír Karas was being developed in a quite intensive way. Since the second half of 70s the very intensive research focused primarily on investigating biomechanical contents of traces began. The research was aimed not only at geometric features of biomechanical contents but particularly at geometric and dynamic characteristics of bipedal locomotion. The relations were elaborated for a vast complex and locomotion in various dispersive environs.

Biomechanics applications in criminalistics were being developed thanks not only to a small enthusiast team of VŠ SNB criminalistics department and department of biomechanics, anthropology and anatomy of FTVS UK in Prague but also there was a significant contribution of other institutions as follows: the Institute of Theoretical and Applied Mechanics of the Academy of Sciences, specialized departments of engineering and construction faculties at the University of Technology, Medical Faculty, Institute of Forensic Engineering VUT Brno, National Research Institute of Machinery Construction, Research Institute of Rheumatic diseases and also a number of other workplaces. As well as individual members of the Institute of Criminalistics in Prague were involved in the research activities. Within not a very large community of criminalists at VŠ SNB developing biomechanical applications there was formed a central group of biomechanics scientists who worked on mutually interconnected research projects (SPZV, AV). Further they together developed criminalistic biomechanics, biomechanics of musculo-skeletal apparatus, substitution of human body main supporting joints, composite materials needed for orthopedical operations, biomechanics of cardiovascular system, artificial heart, biomechanics of artificial vessels, biomechanics of top level sport and also a number of very useful applications. As an example of rather wide interdisciplinary scientific task of biomechanical applications I give a summation of scientific sections at conferences on biomechanics that are regularly held. They are as follows: Human body model, Biomechanics of musculo-skeletal system, Engineering system of biomechanics, Sports, ergonomic and loading (forensic) applications of biomechanics, Biomechanics of skeletal system, Biomechanics of cardiovascular and respiratory system, Biomechanics of larynx, Modelling of secretory system, Modelling and methodology, Clinical biomechanics.

As the summation of names all of sections indicates current biomechanical applications are considerably branching and heterogenous so that is quite impossible for the individual to be a real expert at workshops of all given sections. The section dealing with forensic biomechanical applications was quite important for criminalistics itself.

Biomechanics community achieved great success of an international importance but they could be hardly listed here in such a brief introduction. So it is possible to say that biomechanical applications progressively transformed into the denomination ”Criminalistic biomechanics”.

Regularly, once in two years international conferences focused on criminalistic, forensic medicine and forensic engineering applications of biomechanics were held. The first conference was carried out in 1976 and the last one in 1990 (December 4). The tradition of conferences was disrupted (that lasted 11 years) in connection with social changes and expert community disintegration in our country. The conference was reinstated in 2001 (November 29) thanks to a few enthusiasts at PA ČR with the aim to restore mutual exchanging of scientific knowledge.

This period could be termed as the outset of biomechanical applications in criminalistics. It is also the period widely aimed at scientific and research biomechanical activities and initial stadium of forensic biomechanics constitution.

### 3. Period – Forensic biomechanics

Forensic biomechanics as a real full-value forensic discipline can be mentioned since 1994 when for the first time in the Czech Republic the biomechanics expert opinion was used as evidence in the course of investigating a crime (Prof. V. Karas). In the second half of 90s forensic biomechanics was stably constituted as a forensic scientific field. As other forensic disciplines so as forensic biomechanics is grounded on a parent field of biomechanics and progresses to forming its own scientific base, development directions and some particular possibilities for using forensic biomechanics in expertising are specified. Forensic biomechanics has profiled as an independent discipline to that extend that in the latest years expert opinions of ”Criminalistics – forensic biomechanics specialisation” sphere are being requested in the course of investigation.

Forensic biomechanics has specified quite clearly its subject of matter and accomplished a cognitive, noetic and institutional function of the scientific field. Forensic biomechanics scientific development is evidently grounded on an expert practice as some problems and issues arise that expert opinions have solved as scientific research orientation itself has been oriented.

Forensic Biomechanics is a scientific field using biomechanics and biomechanics methods on investigating criminalistic traces having biomechanical contents and decoding information of a criminalistic relevant event that has resulted from human being move activities and that has been connected with the investigated event. Forensic biomechanics studies and clarifies the sphere of criminalistic traces having biomechanical contents so the mentioned applications inform of a criminal’s soma or his/her locomotive behaviour. Forensic biomechanics seems to be according to its research subject some kind of intersection between biomechanics and criminalistics. In a creative way it applies biomechanics methods of research, procedures and problem solving on criminalistics problems. Forensic biomechanics studies and investigates a locomotion system and persons locomotive behaviour being connected with a crime and leaving criminalistic traces with coded biomechanical contents in themselves. The term ”forensic” biomechanics has been used for the application of biomechanics on investigating and studying criminalistic traces.

Current Trends of Forensic Biomechanics Applications and Prospects of Forensic Biomechanics Development

Forensic biomechanics uses biomechanics and its methods of knowledge in two important directions:

a) Criminalistic traces having biomechanical contents.

b) Relevant criminalistic changes occuring as a result of a mechanical interaction of ”man-his/her surroundings system”.

In case of forensic biomechanics practical applications the two following directions of research can be indicated on the basis of experience and literature comparison. Both of them differ from each other fundamentally as to the subject matter of scientific and epistemological approach (Porada 1987, Straus 2002):

**1.** Biomechanical contents of trasological traces this research direction has been studied and developed the most intensively for the time being. The reason is that trasological traces of footwear and locomotion traces occur at the crime scenes in 95,5% and also decoded information can be practically usable for the criminalistics practice. Study of biomechanical contents of bipedal locomotion trasological traces has been logically aimed at geometric characteristics firstly, then at the kinematic ones and last but not least at dynamic characteristics. The latest researches show that part of information on biomechanical contents dynamic characteristics can be obtained through study of one barefoot print and so it is not necessary to know parameters of a locomotion path.

Applications are elaborated and worked out to determine the person´s body height with the help of locomotion traces in various kind of a base.

**2.** Biomechanical contents of handwriting traces. For the time being these applications are at their beginning because of uneasy quantification of single characteristics. Most handwriting characteristics have a qualitative character and their qualification mostly causes considerable difficulties. Despite this fact there have been some research trends having a good application for criminalistics practice.

**3.** A study of biomechanical contents of the hands internal sides, palms possibly. This kind of trasological traces have not been studied so far and not even used in the practice because of the lack of information. Traces of hands internal sides and palms have been described in criminalistics literature rather sporadically most of all following the aim to identify the person using the traces left the perpetrator at the crime scene. The criminalistics literature gives options of a person identification using marks of the criminal gripping a murderous item, resting the hands on the pad and last but not least it also indicates ways how to determine anthropometric proportions in case a decaying corpse or skeletal remains have been found.

**4.** The mechanical extreme dynamic loading of an organism. Mostly they are such situations when the assailant attacks a victim by giving him/her a punch or hitting him/her with a stick or another solid item. Most often the attack is directed at the head of the victim. In case of these biomechanical analyses the problem is to assess the fact if the attacked person died immediately or if he/she lived for some particular time so there was some chance to rescue him/her. In essence it is very important to set and quantify the limit that will be crucial for survival under the conditions of a mechanical extreme loading of the victim’s head.

**5.** Biomechanical assessment of falling a victim from high, out of the window most often. From time to time there is a case when an aggressor attacks a victim with the intention of killing he throws him/her out of the window while in the course of the investigation he defends himself/herself claiming the victim has dropped out by himself/herself or the incident has been caused by some misadventure. The biomechanical analysis can judge the issue if the person has dropped out by himself/herself without the fault of somebody else or if at the very moment of falling he/she was given a strength impulse therefore he/she has been thrown by someone (possibly he/she could take off). It is the problem of geometry and kinematics, further the problem of a body gravity center in the course of falling as an open kinematics series.

**6.** The use of biomechanics in motor vehicles construction and their equipment. There is included the investigating of the relations between a mechanical characteristic of the car and the situation when the driver is getting tired, further the seat construction, brakes, securing against the force impulses caused by frontal impacts etc. Other factors are motoric and biomechanical ones such as visibility, reaction capability and the duration of needed movements.

**7.** Biomechanical application in the course of contact combating in self-defense. It is very important for police practice. For self-defense elements it is necessary to know kinematic characteristics of a person reaction from the point of view of an attack and defense. Biomechanical analysis helps to eliminate some imperfections.

We think the indication of these broadly outlined application directions is quite sufficient as a rudimentary orientation. All of biomechanical forensic applications always appear to be a matter of an expert examination and in all probability they will never be a matter of a purely practical use at the very crime scene.

The biomechanical contents of trasological traces seems to be at the current cognition level already finished application of a scientific investigation. At the current cognition level nothing new in these applications could be essentially discovered and in further studies only marginal applications of this research will be specified.

Only as an example the following table is given presenting relations of body height prediction by means of foot length just in the same way as it is presented by the professional literature and determined by the latest studies. It is my belief that the reader may form his own idea of the calculation accuracy.

The tabular summary of the body height calculation $v_T$ (cm) in dependence on the foot length $d_n$ (cm) and width $s_n$ (cm) according to various authors:

| Author (year) | Dependence |
|---|---|
| H. de Parville (1899) | $d_n = \frac{8,6}{30}\left(\frac{v_T}{2} + 0,05\right)$ |
| Feix (1965) | $v_T = 7 \cdot d_n$ |
| Reihard, Zink (1969) | Men<br>$v_T = 95,60 + 2,88 d_n$<br>Women<br>$v_T = 91,10 + 2,84 d_n$ |
| Titlbach (1971) | Men<br>$v_T = 2,5 \cdot d_n + 4,5 \cdot s_n + 64$ |
| Addapted by the author according to Titlbach (1971) | Men<br>$v_T = 4,0064 d_n + 68,012$<br>$v_T = 0,3746 d_n^2 - 16,166 d_n + 338,31$ |
| Straus (2002) | Men<br>$v_T = 3,5026 d_n + 83,883$<br>$v_T = -0,0024 d_n^2 + 3,629 d_n + 81,201$<br>$v_T = 32,005 d_n^{0,5247}$<br>Women<br>$v_T = 2,8789 d_n + 94,038$<br>$v_T = -0,3434 d_n^2 + 18,504 d_n - 83,56$<br>$v_T = 65,548 \ln(d_n) - 45,247$ |

| | |
|---|---|
| Straus (2002) | Men<br>$v_T = 5{,}4778 s_n + 125{,}4$<br>$v_T = 2{,}3519 s_n^2 - 41{,}547 s_n + 359{,}86$<br>$v_T = 91{,}081 s_n^{0{,}2961}$<br>Women<br>$v_T = 1{,}2383 s_n + 149{,}55$<br>$v_T = 135{,}52 s_n^{0{,}0778}$<br>$v_T = 135{,}52 e^{0{,}008 s_n}$ |

On analyzing three significant periods of forensic biomechanics development could be specified as follows:

1. Period – 1889–1971 - The period of anticipating possible coherence, marginal use within trasology – ”Prehistory of biomechanics applications”.
2. Period – 1971–1994 - Biomechanics aplications in criminalistics, separate applications, criminalistics application base developing, criminalistic biomechanics constitution.
3. Period – since 1994 till nowadays - Forensic biomechanics constitution – biomechanics of extreme dynamic organism loading, biomechanics of falling from high and biomechanical contents of traces seem to be the major applications.

As the practice knowledge show and police authorities demand it will be necessary for the future to solve the person identification ossibilities by means of a dynamic stereotype of a person locomotion kinematic series. Some new opportunities emerge in connection with iomechanical contents of trasological traces as kinematic and geometric analysis of a person locomotion kinematic series. The problem is that the perpetrator is being recorded by camera from a longer distance in the course of his/her locomotion so the person could hardly be identified in another way but a geometric and kinematic locomotion series must be used. In this case the dynamic stereotype – person locomotion habit is being identified in essence. Some analogy can be found in a person identification according to his/her handwriting.

Further forensic biomechanics will mainly be oriented on a biomechanical analysis of an extreme dynamic loading of the organism, particularly the prediction of forces directed against the victim body, mainly against the head. Analyzing these facts the critical limit of a short-term affecting violence in case of survival or temporary survival will be determined precisely. As well the biomechanical analysis could be used in resolving victim falls from big high and by decoding forces, geometry and kinematics of a body gravity center trajectory at the very moment of falling the involvement of the other person could be judged. The research will also be oriented on solving not so far investigated characteristics of trasological traces biomechanical contents, particularly traces in a dispersive environs, various topographical conditions and trasological traces fragments.

The research aim is to achieve such model situations for conducting at the crime scene – what should be secured, measured, documented so the biomechanical analysis could be carried out on this basis.

The development of current forensic biomechanics has been influenced significantly by expert activity in this sphere. Forensic biomechanics applications start taking a significant position in criminalistics. In a number of cases the expert opinion on the subject field of criminalistics –forensic biomechanics specialization has been demanded and just the conclusions of the biomechanics expert have helped to unravel objective facts and to assess the state facts of the crime. The present situation indicates that biomechanical assessment of an organism extreme dynamic loading and falls from high will play a significant role. In these intentions further opportunities for scientific studies and forensic biomechanics development could be expected.

So the demands and problems of the practice determine further research activities. On the basis of analyzing all expert opinions on forensic biomechanics specialization that have been done in recent 8 years (83 expert opinions) and comparing foreign sources I would like to outline further prospects of forensic biomechanics development.

## 1.4 Extreme dynamic loading of organism

The current expert practice in the sphere ”Criminalistics - forensic biomechanics specialization” deals most often with the cases of the head dull injuries. They are violent crimessuch as murders or attempted murders. These cases are obviously very serious and also the expert opinion proves to be quite often very important evidence in a trial.

A skull injury by a blunt item belongs to injuries we encounter in criminalistics very often. Dull head injuries are significant because of its exposed position and also for that fact in the course of attacking that part of the body containing a vital organ always becomes a target of the assailant. In biomechanical assessment of the skull injuries it is necessary to take into consideration that the skull fracture itself need not result in serious brain and meninx injuries but on the contrary it could be a fatal injury even though there was no skull fracture. All skull injuries are always connected with some kind of brain damage. Every skull injury is considered as a dull skull injury except cut, slash and stab injuries while in the course of that the hit is carried out with a flat of the blunt item in the process of which the application of external striking force by the flat of a striking item is essential. In assessing a fatal skull injury caused by a blunt item the issue, if the hit directed against the skull was fatal and by what force was carried out, is always solved (see chap. 3).

## 1.5 Biomechanics of falling from a high

Falling from high appears to be the sphere of forensic biomechanics has not been examined so much yet. An accident, murder or suicide could result in falling from high. In falling from a relatively low high the body center gravity falls in a parabola while the falling from a big high (when the air resistance is necessary to be considered) is carried out in a ballistic curve. The distance between the jump and impact scenes and also a high belong to major factors indicating the motive of the victim. The assessment of a particular trajectory of the fall in biomechanics analysis can serve as key information for the determination of the way of dying.

Objective solving of the issue of a high and the kind of falling can be done by two ways in essence. The first way is grounded on creating a mathematical model and simulating a fall trajectory and a body position on impact while the second one is grounded on making an experiment and simulating fall with the help of an appropriate model of a human. It is possible for the model to let it fall from some high and consequently judge the fall and impact conditions. Then it is optimal to compare theoretical simulation with experimental data of a biomechanical model falling for the purposes of getting serious scientific knowledge.

If we summarize the current state of forensic biomechanics from the point of view of history, we can state, that forensic biomechanics is a relatively young field in forensic sciences.

Biomechanics was first used on a very marginal basis to solve problems in forensic science, and scientific research on biomechanical applications was developed in the 1960s and 1970s (Karas 1978, Porada 1987). At that time, the first "forensic" visions at the Department of Anatomy, Biomechanics and Anthropomotorics of the FTVS UK in Prague were created, which were of a more intellectual nature. In the forensic community, the term Forensic Biomechanics has begun to be used only since the early 1990s, when this scientific discipline has been used as an expert field. In the second half of the 1990s, forensic biomechanics began systematically developing at the Department of Criminalistic of the Police Academy of the Czech Republic in Prague. The research of the Department of Criminaalistic was based on the scientific knowledge of the past years founded by prof. Viktor Porada, who was a collaborator of prof. Karase, and in his scientific studies, he laid the basic ideas of biomechanical applications in the field of criminalistic and conducted a number of experimental researches. Finally, prof. Porada and prof. Straus at the University of National and World Economy and currently at VŠFS.

Like other forensic disciplines in general, forensic biomechanics is based on the biomechanics of the mother and generates knowledge from the practice and develops its own scientific research base, directions of development and specifies the possibilities of using forensic biomechanics in the expert activity. Forensic biomechanics has become so profound as a separate discipline that in the last years, experts from the field of "Criminalistic - Specialization of Forensic Biomechanics" are already required in the process of proving and investigating criminal activities.

The breadth of the biomechanical content of the forensic trail is determined by the number of traces that can be found in the trail and which provide information on the group or individual characteristics and the motor behavior of the unknown offender who caused the traces.

Opinions on defining the term "forensic biomechanics" are different and many definitions can be found in the literature, only the most frequently used are the following:

Forensic biomechanics applies biomechanical principles to the problems encountered in court practice, both civil and criminal. He studies the mechanics of movement, especially the movement of the muscular apparatus. For criminal proceedings, it provides information on how the injuries could be wounded in violent attacks, suicides, mass abusers and murders, as well as on whether the person's movement was feasible without a stranglehold. In civil proceedings, it can be used to assess falls without witnesses. Forensic biomechanics are based on physical principles and include solutions using computations, often also computer models (Bell 2008).

Forensic biomechanics applies the knowledge of mechanics to answer important questions of criminal and civil law, thus addressing issues related to biological objects, especially the human body (Schneck 2010).

Forensic Biomechanics is a science applying biomechanical theories and technologies to solve problems related to mechanics in the process of expert activity. It was created as a new branch of modern biomechanics as well as forensic science. This is a very potential area of injury research (Xu, Fan, Yu 2010).

Forensic Biomechanics combines the knowledge of mechanics, biology, human anatomy, and physiology to assess events and acts of all sorts - injuries caused by treble, standing, slipping, etc (Engin, 2005).

Biomechanics is a science dealing with the mechanical principles of a living organism. It is one of the most exciting and fastest growing sciences. In forensic sciences, it is biomechanics that explain body wounds at crime scene and help to explain blood drops (Kieser, Taylor, Carr 2012).

Generalizing the considerations of the cited and other authors, the term forensic biomechanics can be defined in relation to the criminology as follows:

Forensic Biomechanics is a science branch that applies biomechanice and biomechanical methods for investigating criminological traces with biomechanical content and decoding information from a criminally relevant event that arose as a result of human activity and related to the event under investigation. Forensic Biomechanics investigates and clarifies the circle of criminological traces that contain biomechanical content, so the applications give information about a human's movement apparatus or behavioral behavior.

Forensic biomechanics is the subject of its research in the common penetration of biomechanics and criminology. In a creative way, she applies biomechanical methods of investigation, procedures and ways of solving biomechanics on the issue of forensic science in connection with the proving of criminal activity. Forensic Biomechanics studies and examines the movement system and the movement behavior of persons associated with the crime and leaves criminological traces that have encoded biomechanical content.

The subject of criminology, as any other science, is determined by a certain kind of the examined laws of the objective world. In the case of forensic biomechanics, the object of investigation can be defined in two directions. The subject of forensic biomechanics research is:

1) Criminological traces with biomechanical content.
2) Criminally relevant changes that arose as a result of the mechanical interaction of the "human-environment" system.

As a practical application of Forensic Biomechanics, based on the experience gained and the literary comparison, we can present the current directions of research, which differ principally from the content of the scientific and gnosological approach (Porada 1974, Applied Biomechanics, Straus 2001, Forensic Biomechanics, Porada, Straus 2001, Criminalistic and Forensic Biomechanics):

1) Biomechanical content of trace logs.
2) Biomechanical content of handwriting marks.
3) Study of the biomechanical contents of the inner side of the hand or palm.
4) Mechanical extreme dynamic loading of the organism.
5) Biomechanical assessment of falls from victims.
6) Use of biomechanics in the construction of motor vehicles
7) Biomechanical aspects of dealing with motor vehicle traffic accidents.
8) Biomechanics of confrontation in self-defense.
9) Identification of persons according to biomechanical locomotion analysis.

Practical use of forensic biomechanics is the most common in assessing falls from heights, non-cascading falls of the human body from relatively small heights (43%) (down to 150 meters where air resistance can be neglected). Furthermore, in cases of extreme dynamic load of the organism (25%) and as a third part of the application, falls from standing to the ground or stairs with drops (15%).

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# 2 Criminalistic biomechanics

## Introduction

Recent progress in the theoretical basis of the science of criminology has inevitably led to the application of biomechanics within the framework of the disciplines constituting the theoretical and experimental foundations of criminology and, subsequently, also its practical implementation at a basic level.

The application of biomechanics to criminalistic has been especially effective in the following areas:

1. The theory and practice of the methodologies of technical criminalistics, analysis of traces of crime, and the theory of technical means of criminalistic identification.
2. Road transport safety legislation.
3. The theoretical foundation and methodologies of special physical training.

Current applications are primarily aimed at the development of both the theory of criminalistic methods and techniques for their practical implementation, as well as at the analysis of the traces of crime and of the technical means of criminalistic identification, in the field of which special attention has been devoted to methods of complex evaluation of traces and to balistics.

The manner in which an individual criminal act is committed is of principal importance for its eventual discovery, investigation, and also prevention. During the investigation process itself, the motorial habits of the criminal represent a set of characteristics of paramount importance. It is self-evident that these habits are reflected the traces left by the criminal during his locomotion at the scene of the crime.

Since a criminal act is to perceived as one among many concurrent material processes of objective reality, it must be appraised as a section of a set of interdependent events, each reflecting the other phenomena of the set being considered and, on the other hand, affecting them to a certain extent. The material outcome of this mutual dependence is manifested through changes in the environment. Biomechanics deals with the changes caused by man.

The capabilities of biomechanics in its specific application to the theory and practice of criminalistics have been listed by Porada (1977). The criminalistic aspect of analysis of bipedal locomotion has been treated in monographs by Karas (1978), and Porada (1987) and also in the theoretical analysis of bioballistics by Liška (1980).

An extensive application on the biomechanical approach seems to be justified mostly in the areas of theoretical analysis and practical evaluation of material traces of criminal acts, of criminalistic identification, and for the development of some specific criminalistic techniques.

Here it is possible to proceed from the current understanding of the category of a trace of a criminal act, as well as from the currently used classification of traces, employing the conventional interpretation of the information content of a trace. The actual applicability of biomechanics is primarily dependent on the so-called biomechanical content of a particular trace. Generally speaking, all traces of a criminal act which have originated during the interaction between a man and his environment, either organic or inorganic, have a certain biomechanical content, more or less apparently dependent on the possible use of tools by the criminal etc.

This biomechanical content is lacking, for example, in the case of traces that originate during the mechanical interaction of inorganic bodies. Typical examples of the final stages of these interactions are represented by the traces of destruction resulting from a projectile hitting a wall, or that occurring in a car crash.

The biomechanical content of traces becomes immediately obvious in the identification of a criminal by analysis of traces left by shod or bare feet, or of other similar imprints. Such tracks originating during the interaction of forces between the foot and its pad, while the person is standing, walking, or running (static or dynamic tracks) are amenable to analysis by biomechanical methods. Further studies in this area should certainly help to elucidate the existing mutual dependence between the geometric configuration of a set of tracks left by a criminal during his movements at the scene a crime and some of his body characteristics, such as the physiological characteristics of his legs and feet, body height, body mass etc.

Also in the area of criminalistic ballistics, the biomechanical content of traces is quite apparent, especially in the analysis of injuries caused by projectiles and of the overall effects of firearms. This area is quite extensive, comprising descriptive information on injuries caused by projectiles, together with their classification, and specific features of each group as well as methods of assessing the trajectory of the projectile, both in the body and in the surrounding space, with special emphasis on locating the exact points where the projectile entered and left the body, and on evaluation of its impact on various organs. It must be assumed that any exact solution to the above problems must be based on analysis and application of the general principles of a number of physical and biological phenomena, and that it must use approaches typical of a large number of disciplines which, by their nature, are concerned with the problems of criminalistic balistics only marginally, i.e. medicine, and especially surgery, all specialized branches of balistics, comprising internal, transitional, external, and terminal balistics, military science, criminology, to name only the most important. Basically, however, the problem of the interaction of a projectile with a human or animal – body remains a biomechanical one.

Biomechanics is capable of providing deep understanding in a number of areas of both criminalistic theory and practical implementation of criminalistic techniques, i.e. above all:

- in improving the level of theoretical analysis and experimental data concerning the aetiology of criminalistic traces with biomechanical content;
- in adding a necessary measure of exactness to the geometric, kinematic, and dynamic analysis of traces with biomechanical content, and in introducing new methods of quantification and assessment of these traces;
- in deepening the level of knowledge of the specific mechanism of interaction between the human body and external objects in the case of projectile penetration.

The improvements described above would then facilitate the formulation of corresponding technical procedures applicable to the detection, documentation and evaluation of traces that are due to biomechanical interactions. Such an approach is intended to be employed in both criminalistie practice, as for example in expert analysis, and in the region of applied biomechanical research within the theory of criminology. At the same time, it can be expected here that the currently used technical means of measurement and documentation of traces will not be sufficient for an adequate assessment of the biomechanical content of traces. With regard to this, new methods in this field should be developed, especially those of stereo photogrammetry and holographical interferometry, together with some methods combining numerical and graphical approaches.

## 2.1 Biomechanical analysis of tracks of human locomotion

Analysis of the biomechanical content of tracks of human locomotion together with its quantitative evaluation reveals a novel facet of one large group of criminalistic techniques which has until very recently, been, considered to consist of exclusively empirical methods, for which no exact substitutes were deemed to be possible. However, the biomechanical analysis of tracks has demonstrated that many of the hitherto neglected phenomena contain a measure of information valuable from the point of view of further investigation and for the search for the criminal. This is why certain technical assessment procedures of this type of trace should be altered.

A successful interpretation of the information carried by a specific track is determined by the level of our knowledge of the relationship between the mechanical impulses directed from the criminal towards his environment, on the one hand, and the responses of this environment, represented by a characteristic track, on the other. We must nevertheless bear in mind that a certain ambiguity in the relationship between the cause and its effect has been demonstrated to be intrinsic for traces of this kind. In the first approximation, a better understanding of this complex relationship can be achieved by the adoption of the notion of secondary modification – for example, by the properties of the pad in the ease of walking tracks – of the primary interaction between an impulse and its response (Pješčak 1982).

The need for analysis of tracks of human locomotion is indisputable. The vast majority of delinquents – 95.5% – leave the scene of the criminal act on foot, either walking or running, only a few of them use some means of transport (Protivinský, Balík 1972). The extent to which the biomechanical content of a track is apparent depends on the number of specific discernible features of the track that are capable of indicating the corresponding global and individual characteristics of the criminal and also the pattern of his motorial behaviour. Every analysis of this kind must inevitably proceed from a complex assessment of all the detection features in all their possible correlations. This is why a generalized systematic approach to the evaluation of sets of tracks, using a corresponding matrix of features of the set, is required.

## 2.2 Biomechanical content of tracks of bipedal locomotion

During a close study of the tracks of human locomotion, both practical experience and logic lead us to assume that all material changes to the objects bearing the tracks reflect a certain portion of the somatic characteristics and pattern of the motorial behaviour of the individual whose action created the track. Such a record of some of the biological attributes of an individual, together with his actual behaviour at the moment of the interaction that created the track, can be considered to represent the biomechanical content of the track. In this category belong primarily the geometrical, kinematical, and dynamical features of tracks.

The geometrical features will be found mostly in the spatial configuration of a track, or a set of tracks (a trail of locomotion), the most important characteristics being here those of length, width, and area of the track, or its depths (volume) in the case of plastic tracks, together with spatial correlations of a set of tracks, both in terms of distance and angular data. Also data describing the symmetry - or asymmetry - of the above mentioned parameters belong to this group.

The kinematical features will be manifested primarily in the frequenee of the tracks, and from the correlation of these with other factors involved in the complex assessment of a track and of a set of tracks, the principal parameter of the velocity of the locomotion will be inferred.

Dynamic features involve the deformation of the pad caused by forces acting at the time the tracks, were mode with special emphasis on detailed study of the boundaries and central parts of the tracks, capable of indicating the various degrees of rolling or skidding involved in the motion, local compression of material etc.

Utilization of the above features of the biomechanjcal content of tracks for both the identification of the individual and a description of the actions during which a particular set of tracks originated becomes possible only after complex analysis of the given set, usually also involving evaluation of the mechanical properties of the surface bearing the tracks. Outdoors, a proper evaluation of the character of the ground, of its inclination, especially with regard to the direction of locomotion, and of the evened of its surface is equally important.

The extent of the biomechanical content of a specific trace is determined by the number of detectable features which can yield information on global and individual characteristics of the individual and on his behaviour.

According to the current practice, only information inferred from the static analysis of tracks has been used in the process of criminalistic identification. Analyses of tracks of locomotion on a more complex level, involving also the appraisal of various aspects of the processes involved in forming the tracks, and using methods directly applicable during the investigation, have rarely been used so far. Valuable additional information on the behaviour of the criminal at the scene of his act, and on some of his characteristics would therefore have been lost in each case.

## 2.3 Generalized system and matrix of features of a set of tracks of human locomotion

### 2.3.1 Definition of a generalized system of a set of tracks of locomotion

By $m_1...,m_l$ we denote all identification features which can be detected – or at least theoretically assumed – for a set of sequential tracks of human locomotion. Let *M* be a non-empty set containing these features, i.e.

$$M = \{m_1...,m_l\}; \ l \geq 1.$$

Identification of an individual is possible provided the features contained in a non-empty set $M_1 \subset M$ specific to each individual case are known and, moreover, numerically evaluated. The set *M* represents the required and sufficient condition of identification, defined separately for each ease.

Further we assume that there exist relationships $g_1, ..., g_f$, $f \geq 1$ describing correlations between elements of the set *M,* and relationships $g_{f+1}, ..., g_m$, $m \geq f+1$, accounting for bonds between elements of the set and factors outside the set.

The non-empty set of these relationships has been denoted as

$$G = \{g_1, ..., g_m\}.$$

The generalized system of features of a sequence of tracks can then be defined as a non-empty set S. comprising both the set *M* of identification features and the set G of characteristics of the system, given by the existing relationships between the input and output variables of the elements of *M,* and between them and the assumed external factors, i.e.

$$S = \{M, G\}.$$

The system defined above is an open system a stochastic nature. Elements of the space of the system constitute an open set and their definition can never be considered as entirely complete.

### 2.3.2 Structure of the system of features of a set of tracks of locomotion

On a basic level, the space of the features of the system can be divided into three categories: geometric features, kinematic features, and dynamic features. This basic categorization is helpful for a systematic treatment of the subject, since it provides a basic orientation within the system. The following notation is to be used (Porada 1987):

$m_1,...,m_g$ – geometric features,
$m_{g+1},...,m_k$ – kinematic features,
$m_{k+1},...,m_d$ – dynamic features.

These sets of features form non-empty subsets of *M*

$$M_g = \{m_1,...,m_g\}$$

$$M_k = \{m_{g+1},...,m_k\}$$
$$M_d = \{m_{k+1},...,m_d\}$$

The corresponding relationships between elements of these subsets and external factors are grouped into the subsets Gg, Gk, and Gd, such that:

- $g_1, ..., g_{vg}$ representing correlations between elements of Mg and factors external to it, constitute the subset

$$Gg = \{g_1, ..., g_{vg}\};$$

- $g_1, ..., g_{vk}$, representing correlations between elements *of* $M_k$ and factors external to it, constitute the subset

$$G_k = \{g_1, ..., g_{vk}\};$$

- and $g_1, ..., g_{vd}$,standing for the bonds between the elements and external factors of *Md* form the subset

$$G_d = \{g_1, ..., g_{vd}\};$$

By utilizing the above defined subsets of elements of *M,* and the subsets of correlations of G, the following subsystem of the system S can be defined:

— the subsystem of geometric features of tracks of locomotion

$$Sg = \{Mg, Gg\};$$

— the subsystem of kinematic features of tracks of locomotion

$$Sk = \{Mk, Gk\};$$

— the subsystem of dynamic features of tracks of locomotion

$$Sd = \{Md, Gd\}.$$

The following conditions hold for these subsets:

$$S_g \subset S \wedge M_g \subset M \wedge G_g \subset G;$$
$$S_k \subset S \wedge M_k \subset M \wedge G_k \subset G;$$
$$S_d \subset S \wedge M_d \subset M \wedge G_d \subset G.$$

For further analysis, it is necessary to study both the space of features and the characteristics of the systems of features of sets of tracks.

The individual relationships and bonds between specific elements of the system will be expressed by the matrix of the basic structure *Wb.* The structure of an arbitrary system of features of tracks of locomotion can be described by its structure matrix *W*:

$$W = \begin{bmatrix} w_{11}, w_{12}, \ldots w_{1n} \\ w_{21}, w_{22}, \ldots w_{2n} \\ . \\ w_{n1}, w_{n2}, \ldots w_{nn} \end{bmatrix}$$

This matrix is a square matrix of the type *(n, n)* and its elements denote the bonds between pairs of elements of the system of features. Any change to the discriminatory level of the system, or on its part, is reflected in this matrix by a corresponding change in the number of rows and columns of *W.* which causes only a minimal amount of formal difficulty. A qualitative description of the structure of the system is provided by the so-called matrix of basic structure $W_b$, the elements of which indicate the existence (or non-existence) of an actual bond between two elements of the system. It is usual to use the common logical symbols 1 and 0 in order to express the existence of a bond mathematically; the following matrix can then be regarded as an example of the matrix of basic structure of a system:

$$W_b = \begin{bmatrix} 1,0,1,0,0 \\ 0,0,1,1,0 \\ 0,1,0,1,1 \\ 0,1,1,0,0 \\ 0,1,0,0,0 \end{bmatrix}$$

The properties of individual bonds $W_{i,j}$ between two elements of a system structurally defined by its matrix of basic structure can be further described in more detail by a system of square bonding matrixes of elements of the system of identification features. Each of these bonding matrixes, $W_{i,j}$, obtained separately, can be substituted into the initial structure matrix of the system *W.*

Three basic submatrixes can be defined in the first approximation within both the structure matrix a system and the corresponding matrix of basic structure according to the above categorization, these being the submatrix of the geometric features of locomotion, $W_g$, the submatrix of the kinematic features of the tracks of locomotion, $W_k$, and the submatrix of the dynamic features of the tracks of locomotion, $W_d$ . In the matrix of basic structure of the geometric features of a track, the rows and columns represent individual geometric features as elements of the matrix $M_g$. Analogously, elements of sets $M_k$ , $M_d$ are represented in matrixes of basic structures of kinematic and dynamic features. The matrix of basic structure of the entire system can be schematically expressed in terms of the individual submatrixes as:

$$W = \begin{bmatrix} w_g,1,1 \\ 1,w_k,1 \\ 1,1,w_d \end{bmatrix}$$

## 2.4 The mechanism of the origin of a track

Specific individual features of the mechanisms of walking, running, and jumping are all reflected during the processes producing a track. Detailed analysis, for example, reveals, why a track originating in walking is less distinct in the central area of the imprint of the shoe, or the bare foot, while both the heel and tip are more prominent in both cases (Fig. 2.1).

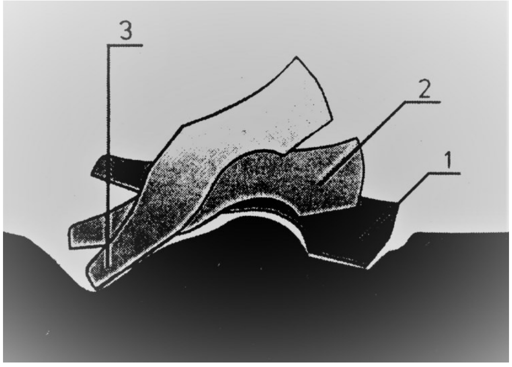

Fig. 2.1. A Schematic representattion of the mechanism producing a plastic of a shoe in its three phases; 1 - deformation caused by the heel; 2 - deformation caused by the shank of the shoe; 3 - deformation caused by the tip of sole (Porada 1987).

Both the general aspects and individual modifications of bipedal locomotion form the basis of the analytical evaluation of tracks of shod or bare feet. For example, the human gait can be characterized by the following parameters: the length of the step, the position of the soles, the distance between the imprints of the left and right feet, the angles made by the imprints of soles with the general direction of walking etc.

The process of formation of a track, or of a set of tracks, during locomotion can be assumed to differ for individual mechanisms corresponding to the kind of locomotion, the material of the surface, the general situation at the scene of the criminal act, the load carried, and a number of other factors.

Each track represents a change to the material of the surface, originating from the interaction between two entities: the reflected individual and the reflecting environment. During this interaction, the reflecting environment is altered to a certain extent, discernible by subsequent analysis. All cases where also the properties or external configuration of the reflected individual undergo changes are not going to be treated in the present analysis. The problem in question is one of analysis of the concurrent reflection of both the external attributes of an individual and his functional and dynamic features, abilities and habits.

In order to achieve detectable changes in the studied environment, seen as the reflecting subsystem, the following general conditions, known from criminalistic literature, must be that:

The interaction between the reflecting and reflected subsystems must be sufficiently intense.

The interacting objects must be heterogeneous regarding their physical, mechanical, and chemical properties. This condition is, as a rule, met in all cases of application, as the systems of properties of two or more interacting objects are rarely identical.

The final effect of an interaction of these objects must be fixed by either material changes in the reflecting object or changes in its properties or structure, while these changes should be detectable by currently used criminalistic techniques and methods.

However, all material changes in the reflecting object, externally detectable, must be accompanied by alterations to the structure of this object, or to one or more of its properties. Each new property of an object, differing from previous properties, and due to either natural or artificial processes represents in itself a change in the properties of the object. For example, the occurrence of a plastic track – so-called volume track – instead of a planar track is dependent only on the intensity of the force interaction and the material properties of the reflecting object.

## 2.5 Schematic expression of a set of traces of human locomotion

For further deeper understanding and also with regard to the process of identification itself, a certain schematic pattern for expressing human locomotion is required that allows for simple and accurate representation of all manners of locomotion of individuals encountered in criminalistics. A simple schematic notation of locomotion can serve as the necessary source of readily available information on the manner of locomotion of the individual in his specific environment and also on the elements and their mutual correlations of the previously defined system (Porada 1987).

In our analysis, the category the step of the human gait will comprise not only the geometrical distance between the feet, or their imprints, but also the duration's of the corresponding motions.

The notation used for this purpose is as follows:

$t_L$, $t_R$ - duration of the entire step of the left and right leg, correspondingly;
$t_0(L — R)$, $t_0(R — L)$ - duration of the push-off from the left to the right leg, and vice versa, where the existence of a flight phase represents a necessary condition;
$t(R + L)$ - time spent of standing on both feet when the individual does not move, which can be equivalently expressed as
$t(L + R) \Leftrightarrow t(R + L)$;
$t_{do}$ (R — L), $t_{do}$ (L — R) - time spent supported on both feet during the transition from the right foot to the left foot, and vice versa, which applies only for those types of gait for which this phase actually exists;
$t_0(R)$, $t_0(L)$ - duration of the monopedal phase on the right and left leg respectively, for running $t_0\,(R) \Leftrightarrow t_R$;
t(R), t (L) - time spent standing on either leg;
t(x) - duration of a period of either support or locomotion other than in the manner described above, such a support by hands only etc.

Utilizing the above notation, the human gait can be described by the set of relationships

$$t_p = t_{do}(L - P) + t_o(P) + t_{do}(P - L),$$

$$t_L = t_{do}(P - L) + t_o(L) + t_{do}(L - P).$$

The inequality $t_{do} > 0$ is characteristic of walking. Generally, the faster the gait, the shorter the interval $t_{do}$, although it always remains larger then zero. Also the character of the geometric, kinematic, and dynamic features of the traces of locomotion corresponds to this in each particular case. According to Janda et al. (1966), the aproximate relationship

$$t_{do}\,(P - L) = t_{do}\,(L - P) = 1/10\ t_p = 1/10\ t_L.$$

is valid.

The equivalent notations for walking (a) and running (b) can be expressed as:

$$(a) \quad t_p \cap t_L \neq \varnothing,$$

$$(b) \quad t_p \cap t_L = \varnothing.$$

All the basic patterns of human locomotion can be schematically expressed by means of these symbols. For example:

a) slow walk:

$$t\,(P + L) \rightarrow t_o\,(L) \rightarrow t_{do}\,(L - P) \rightarrow t_o\,(P) \rightarrow t_{do}(P - L),$$

b) fast running:

$$t\,(P + L) \rightarrow t_o\,(P - L) \rightarrow t_L \rightarrow t_o\,(L - P).$$

A more complex utilization of this approach to the representation of the various possible patterns of locomotion of an individual, together with the notation of the transitions between the individual phases of the locomotion studied, and some specific details, such as lines of entry and departure of the criminal, and his movements at the scene of the crime, are shown in Figs. 2.2, 2.3.

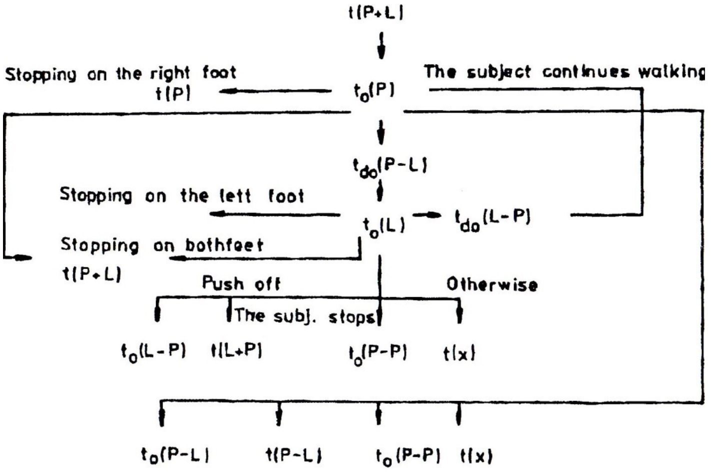

Fig. 2.2. Schematic representation of a period of walking, and some other ways of consequent locomotion.

## 2.6 Tasks and possibilities of identification by the analysis of tracks

A single track, or a set of tracks or locomotion can contain important data from the point of view of the process of identification of groups and individuals. The following data on the individual are of major significance for the identification process:

- somatic data on the individual (body height and weight, sex, age, specific features of body build, such as laterality, symmetry, and alterations to some functions of motion;
- data on the motorial behaviour under specific circumstances (the velocity of locomotion, physical ability, the degree of training) as well as other aspects of the motorial behaviour of the individual, such as waiting, hesitating, hiding, etc.; data on the individuals dress and the use of various other objects (shoes, boots, a stick etc.);
- data revealing intentional mystification (by shoes, damaging the tracks, or by alternations of the habitual pattern of motion);
- data on the various physical effects changing the tracks left by the criminal (e.g. water, atmospheric effects, aging of tracks, superposition of other tracks, properties of the material in which the tracks had been left etc).

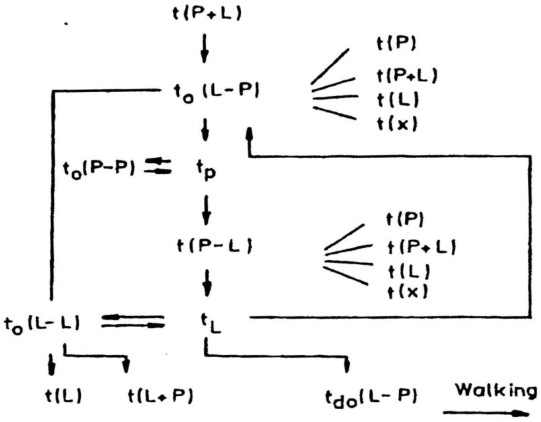

Fig. 2.3. Schematic representation of running showing a possible transition into walking.

The above information, crucial for any identification process based on the analysis of tracks, cannot usually be derived from the track directly, but it can be possible to obtain it by complex analysis of the mechanical features into which some of the external features and patterns of motorial behaviour of the criminal can be projected. These individual pieces of data are elements of the comprehensive information which, as a whole, forms the basis of any group or individual identification. For information to be gained from the study of specific features of a track, the necessary relationships between the relevant variables must be known, which, on the one hand, are capable of expressing the significant properties of the subject, and facilitate the actual mechanical analysis of the track, on the other. These properties are all stochastic in nature, the approximation of which can be obtained by means of appropriate experiments.

Both basic and applied research have to date been able to provide only marginal results that are reliable enough for use in the process of identification. Current theoretical and experimental knowledge in the fields of biomechanics, mechanics, physics, psychology, and anthropology, and knowledge obtained from practical investigations, actually do provide approaches that are applicable in some areas with a considerable degree of success. However, these are mostly of a general, fundamental nature, or they represent applications that only partial use the theory of traces for criminalistic identification. Apparently, it is the task of specific research activities within the science of criminology to solve the unique problems of this kind of application, possibly in appropriate cooperation with the other branches of science listed above.

### 2.6.1 The relationship between tracks of the feet and body height

Among recent works that have broadened the so far sparse basis for the analysis of the biomechanical content of tracks, enhancing the possibilities of criminalistic identification by these means, the most notable is that by Titlbach et al. (1971). The authors of this study have treated the question of the existence of relationship, and their numerical expression, between the dimensions of the soles of the feet and body height, between the dimensions of soles and shoes, and between the sizes of shoes and body height. The statistical analysis of this problem involved the following parameters: body height, mass of the body, length of the sole of the foot, width of the sole, shoe length, shoe width, shoe type, age. The individual geometric somatic parameters were measured either by common anthropometric methods or by means of a special device for the measurement of the dimensions of the soles of feet. These experimental data provided the basis for an evaluation of the statistical characteristics of the random variables involved. i.e. their mean values, standard deviations, and the average error in the mean. Furthermore, the length/width ratio of the sole, the difference between the length of the sole and that of the shoe, and the difference between the width of the sole and that of the shoe were computed. Statistical treatment of the final set of data yielded information that seemed to indicate the following correlation’s:

1) Body height depends on both the length and the width of the sole.
2) With increasing body height the length of the sole also increases within a certain scatter band with the average rate of this increase being *2.5* cm/cm (increment of height against that of the length of the sole).
3) A simultaneous correlation’s exists between body height and the width of the sole, the ratio between the increments in body height and the width of the sole being *4.5* cm/cm.

The correlation’s defined above allowed an empirical relationship to be constituted for the prediction of the probable body height of an average individual depending on data on the dimensions of the soles of his feet in the form of

$$v_T = 3{,}1\ d_n + 4{,}0\ s_n + 53\ \text{(cm)}$$

where $v_T$ represents the body height (cm), $d_n$ is the sole lengths (cm), and the width of the sole (cm).

The probabilistic relationship between body height and shoe size was determined in an analogous manner. This correlation can be expressed as

$$v_T = 2{,}6\ d_o + 4{,}3\ s_o + 55\ \text{(cm)}$$

where $d_o$ is the shoe size (cm) and $s_o$ stands for the width of the shoe (cm).

These relationship allow the probable body height of an individual to be evaluated on the basis of numerical data on the dimensions of his feet or on the shoe size. The scatter band of these two correlation's lies within the ± 1 cm limits to the mean curve, which represents acceptable accuracy for practical purposes.

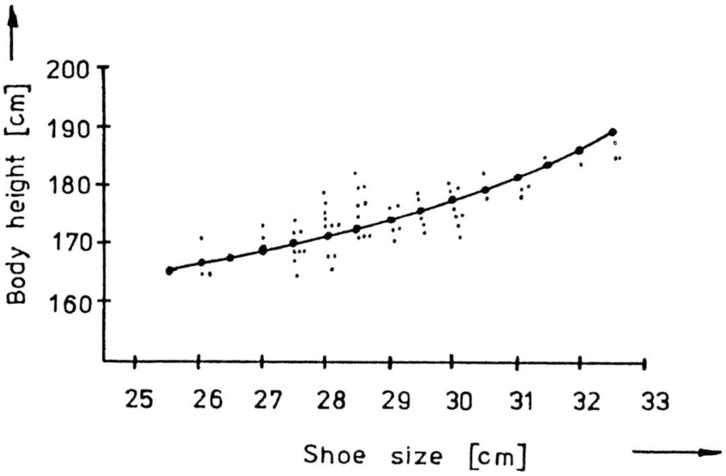

Fig. 2.4. A diagram showing the relationship between foot size and body height (based on: Titlbach 1971).

Other correlation's were further obtained from the available experimental data, the graphical forms of which are shown in Figs. 2.4, 2.5, 2.6. The following curves can be considered as very necessary in practice:

- length of sole against length of shoe; show width against body height; sole length against body height; shoe length against body mass; shoe length against body height; shoe width against body mass; and, finally, the length of a shoe imprint against body height.

## 2.6.2 Basic tasks and possibilities of the analysis of tracks regarding geometry and kinematics

The tracks of human locomotion either singly or in a set – can be treated by various approaches and with various aims. The majority of works containing analyses of tracks of locomotion with respect to their geometry and kinematics have been characterized by a descriptive approach, usually focused on one or an other of the special facets of the problem, disregarding various other important correlation's. At the same time, the practical implementation of criminalistic lacks the appropriate technical means capable of a deeper analysis of tracks and their suitable recording. Similarly lacking are valid statistical evaluations of the measured data, and this, in turn, prevents any verifiable conclusions being made on the basis of this kind of information for use in the identification process. Therefore the expert accounts available to date have been mostly limited to the evaluation of some of the technical parameters of the external composition of the subject, the scope of which does not extend beyond identification of objects (type and size of the shoe sole, specification of the type of shoe, fixation of the track for further analysis, etc.).

The purpose of the following paragraphs is to present briefly some of the new approaches in the criminalistic analysis of sequences of tracks of human locomotion with the aim of improving the possibility of identifying specific subjects.

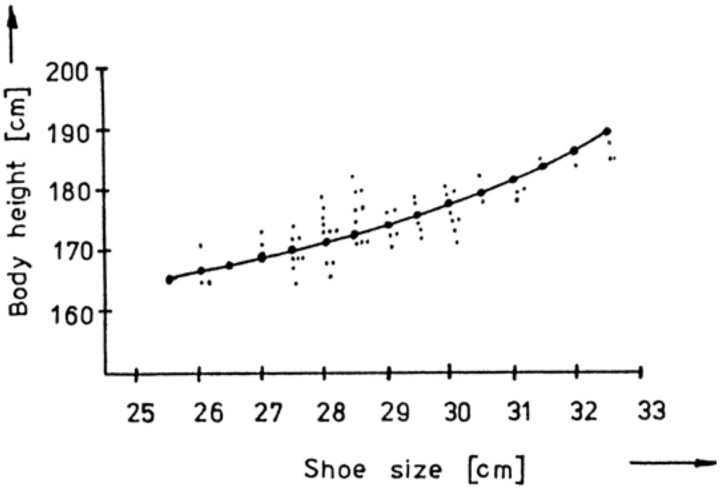

Fig. 2.5. A diagram showing the relationship between shoe size and body height (based on: Titlbach 1978).

Probable height of a walking person (normal stabilized steps, sport shoes with rubber sole; adapted after (h - height of the body; $l_S$ - length of one step; $l_{DS}$ - length of double step; $c_H$-$l_S$ and $c_H$-$l_{DS}$ - correlation coefficients).

| Surface | Linear regression | $c_H$-$l_S$ | $c_H$-$l_{DS}$ |
|---|---|---|---|
| **Linoleum (house; velocity of walking 0,9-1,1 m/s; N=125 men aged 26-41)** | $h = 0{,}297\, l_S + 153\ (l_S < 70\text{ cm})$ | 0,86 | |
| | $h = 0{,}315\, l_S + 163\ (l_S > 70\text{ cm})$ | | |
| | $h = 0{,}157\, l_{DS} + 151\ (l_{DS} < 142\text{ cm})$ | | 0,93 |
| | $h = 0{,}175\, l_{DS} + 155\ (l_{DS} > 142\text{ cm})$ | | |
| | $h = 0{,}153\, l_S + 0{,}083\, l_{DS} + 155{,}5$ | | 0,89 |
| **Cinder (athletic track; N=67 men aged 28-41)** | $h = 0{,}769\, l_S + 115$ | 0,76 | |
| | $h = 0{,}437\, l_{DS} + 103$ | | 0,93 |
| | $h = 0{,}384\, l_S + 0{,}218\, l_{DS} + 109$ | | |
| **Sand (pit; N=67 men aged 28-41)** | $h = 0{,}497\, l_S + 136$ | 0,78 | |
| | $h = 0{,}392\, l_{DS} + 112$ | | 0,81 |
| | $h = 0{,}322\, l_S + 0{,}196\, l_{DS} + 118$ | | |
| **Snow (soft; N=67 men aged 28-41)** | $h = 0{,}497\, l_S + 136$ | 0,62 | |
| | $h = 0{,}368\, l_{DS} + 117$ | | 0,66 |
| | $h = 0{,}248 l_S + 0{,}194\, l_{DS} + 126$ | | |

***Assessment of the velocity of locomotion*** - The velocity of locomotion can so far be assessed only for the case of locomotion along a planar, horizontal, and stiff surface. There are several possibilities, available in the fundamental research, for an expression of the velocity of locomotion. All formulas listed subsequently require the values of the length of the step – or the jump in the ease of running – to be known prior to assessment of the velocity of locomotion together with information on body height and the length of the leg (measured from the surface to the spina iliaca anterior superior). The former of the two values can be evaluated by analysis of the sequence of tracks studied.

The general expression for the velocity of walking can be written in the form

$$v = f\,(h_{le},\, l),$$

where v - is the velocity of locomotion, $h_{le}$ - represents the length of the leg measured between the surface and the spina iliaca anterior superior, l - is the length of the step.

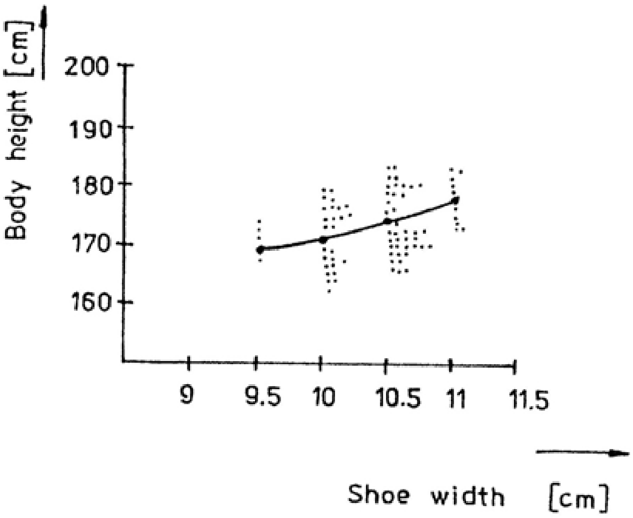

Fig. 2.6. A diagram showing the relationship between shoe width and body height (based on: Titlbach 1978).

The velocity of locomotion expressed in terms of the two parameters defined above is usually gives by the linear relationship

$$v = k_1 \, l + k_2 \, h_{le} + k_3$$

in which $k_1 (s^{-1})$, $k_2 (s^{-1})$, and $k_3 (m.s^{-1})$ are real constants.

**A) Evaluation of the velocity of locomotion**

With regard to application in criminalistic practice, the numerical values of these constants will be specified. From data published by Walt and Wyndham the following expressions for the velocity of locomotion can be derived:

For walking, either

$$v(km/h) = 11{,}63 \,.\, l - 11{,}30 \,.\, h_{le} + 8{,}32$$

or

$$v(m/s) = 3{,}23 \,.\, l - 3{,}14 \,.\, h_{le} + 2{,}31$$

is valid in the range from 0,88 to 2,2 m $s^{-1}$, while for running either

$$v(km/h) = 11{,}02 \,.\, l - 7{,}96 \,.\, h_{le} + 6{,}59$$

or

$$v(m/s) = 3{,}06 \,.\, l - 2{,}21 \,.\, h_{le} + 1{,}83$$

applies for velocities between 2,22 and 3,58 m $s^{-1}$.

Simpler relationship, derived from sets of data by Cavagna and Margaria (1966) can also be used for a first approximation of the velocity of locomotion of and individual in the form of

$$v(m/s) = 3{,}89.\, l - 1{,}41$$

or

$$v(km/h) = 14{,}01 \,.\, l - 5{,}08$$

These two relationship are valid for the range of velocities between 0,83 m $s^{-1}$ and 2,7 m $s^{-1}$. All these correlation's assume that the leg and step lengths are given in meters.

For the sake completeness, the derived formula published by Zaciorski and Kaimin [12], using the time interval of the support phase of walking instead of leg length, will also be given, i.e.

$$v(m/s) = \frac{0{,}5l_0 - 0{,}528}{1{,}1.\, t_0.l + 0{,}31}$$

where $t_0$ - is the length in seconds of the time interval of the support phase, l - again represents the length step in meters.

Neither of the above formulars at our current state of knowledge can be recommended as the one yielding the closets approximation to the true value of the velocity of locomotion, especially taking into account the existing differences between various populations. The final choice must be based only on experimental verification.

As follows from what has been said, the kinematical analysis of a sequence of tracks can be accomplished only after the leg length has been determined. One possible way is to assess this parameter from its correlation whit the body height observed for humans.

**B) Assessment of the length of the lower limb**

These above relationship derived from data published by Walt and Wyndham (1973) include explicitly the parameter of leg length $h_{le}$ (m). According to the data of these authors, there actually exists a correlation between the body height, $h_b$, and the length of the lower limb, which can be given as the linear relationship

$$h_{le} = 0{,}745\ h_b - 0{,}250$$

for which the coefficient of correlation has the value 0,965.

An extensive study aimed at defining the existing mutual correlation's between the geometric parameters of the various parts of the human body has been presented by Ross and Wilson (1974). The basic concept underlying their work is one of thorough statistical evaluation of the proportions of the human body in terms of defined reference parameters. The statistical analysis of their anthropometric data has been used to define an ideal sexless individual, representing a union of parameters of the typical male and female figures. This proportionally "ideal" individual represents the reference model, bilaterally symetrical, the anthropometric data of which correspond to statistically average values for both lames and females, as measured by Garet and Kennedy (1971). The actual difference of an arbitrary segment from its reference value can be expressed by means of the so-called z-index, given by

$$z = \frac{1}{s}\left[ l\left(\frac{170{,}18}{h}\right)^{d} - p \right]$$

where z is the value of the z-index, is the actual value of the parameter describing the part of the body in question, s represents the standard deviation of the experimental set, h is the body height of the individual, d is an exponent the value of which is equal to for all linear parameters, 2 for all data on areas, and 3 for all parameters describing mass and volume; p is a reference value for the particular part studied.

The relationship for the z-index can be employed to assess the length of the lower limb, $h_{le}$, of an unidentified individual for whom the body height is known. Here z will be taken as zero, and hence from

$$0 = \frac{1}{s}\left[ l\left(\frac{170{,}18}{h}\right)^{d} - p \right]$$

follows the sought parameter

$$h_{le}(\mathrm{cm}) = \frac{p.h_b}{170{,}18}.$$

The specific numerical value of the parameter computed according to eqn. Must be regarded as stochastic in nature, and the corresponding standard deviation, s, must taken into consideration. For this model the value of the reference parameter, p, for the length of the lower limb is equal to 96,32 cm.

***Graphical representation of the velocity of locomotion*** - The general relationship (1.2), i.e. $v = k_1 l + k_2 h_{le} + k_3$, will become a function of only one variable for each specific individual, characterized by a fixed value of $h_{le}$. The values of $h_{le}$ considered in the following will be those from the interval, $\langle h_{le\,min}, h_{le\,max} \rangle$, where $h_{le\,min} = h_{le}' - s$, $h_{le\,max} = h_{le}' + s$, in which $h_{le}'$ represents the average value of the parameter for the statistical set and $s$ stands for its standard deviation.

a) The stochastic nature of the velocity of locomotion

Utilizing the anthropometrical data of Ross and Wilson (1974), the above mentioned interval for the length of the lower limb can be written as

$$h_{le} \in \langle 0.92\ \mathrm{m};\ 1.01\ \mathrm{m} \rangle.$$

The relationship between the velocity of locomotion and the length of step can be graphically represented by means of equation for boundary values of $h_{le}$. As can be seen from Fig. 6.7, this dependence can be plotted as a set of parallel straight lines, each corresponding to a different value of the step length. For practical reasons, the graphical representations of the velocity of walking or running based on equations are more easily applicable than those derived from Eqn. since the slope of the corresponding lines appears to be more convenient for utilization of the diagrams. The following linear relationships can thus be derived:

walking:

$$v(\mathrm{m/s}) = 3.23\ .\ l - 0.56, \text{ for } h_{le\,min} = 0.915\ 1\ \mathrm{m},$$

$$v\ (mis) = 3.23\ .\ l - 0.87, \text{ for } h_{le\,max} = 1.011\ 3\ \mathrm{m},$$

running:

$$v\ (\mathrm{rn/s}) = 3.06\ .\ l - 0.19, \text{ for } h_{le\,min} = 0.915\ \mathrm{l}\ \mathrm{m},$$

$$v\ (\mathrm{m/s}) = 3.06\ .\ l - 0.40, \text{ for } h_{le\,max} = 1.011\ 3\ \mathrm{m}.$$

b) A note on the frequency of walking

The formula, together with the relationship proposed by Cavagna and Marqaria (1966), yields for the frequency of walking in the range of velocities

from 0.83 $\mathrm{m.s^{-1}}$ to 2.7 $\mathrm{m.s^{-1}}$ :

$$f(\mathrm{Hz}) = \frac{v}{0{,}362 + 0{,}257.v}$$

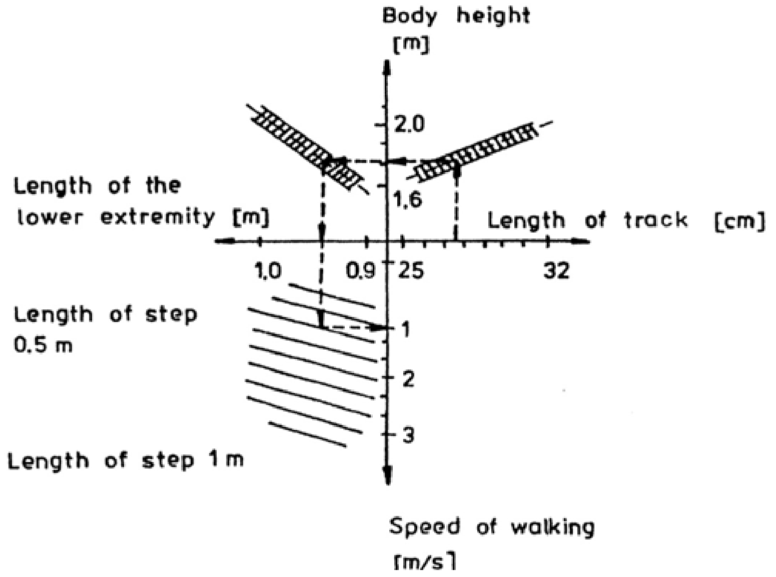

Fig. 2.7. Graphical representation of the correlation's between body height, length of track, length of the lower extremity, and the speed of walking, with the length of the step as a parameter. The method of evaluation of the speed of walking from the remaining variables is indicated by arrows. Body height can be determined from the length of track with a standard deviation of *20* mm, while the standard deviation of the length of the lower extremity, as determined from its correlation with body height, is 48 mm.

Employing the relationship once again, we obtain the following relationship between the frequency of walking and the duration of the support phase, to:

$$f(\mathrm{Hz}) = \frac{0{,}5.t_o - 0{,}528}{0{,}398.t_o.l - 0{,}128.t_o - 0{,}023}.$$

Intentional motions, which include movements of locomotion, are always characterized by significantly lower frequencies than unconditioned forms of tremor (e.g. Jung 1967). The highest frequency of vibration for a tremor has been observed to be in the range of 8 to 12 Hz, while that of unconditioned physiological vibration does not exceed 10 Hz. However, frequencies in the 10 Hz range are not optimal for the execution of intentional motions. Frequencies of approximately 2.1 Hz are considered as the optimum frequencies for the movements of locomotion (for walking, jumping, etc. Haase (1976). The dependence of the optimum frequency on the step length, or the velocity of walking is shown in Fig. 2.8.

Should the length of a bare foot or of an imprint of a shoe be known from the analysis of some tracks, the probable body height of the individual can be determined, and hence also the probable length of the lower limb. From the known length of the lower limb and from the given step length, determined by analyzing the sequence of the tracks of walking or running, the velocity of locomotion can be both computed and plotted in terms of the variables mentioned above. Evaluation of the velocity of locomotion, together with the other defined parameters, can serve as a significant contribution to the identification of the individual being sought, especially with regard to his somatic attributes, patterns of motorial behaviour and physical fitness.

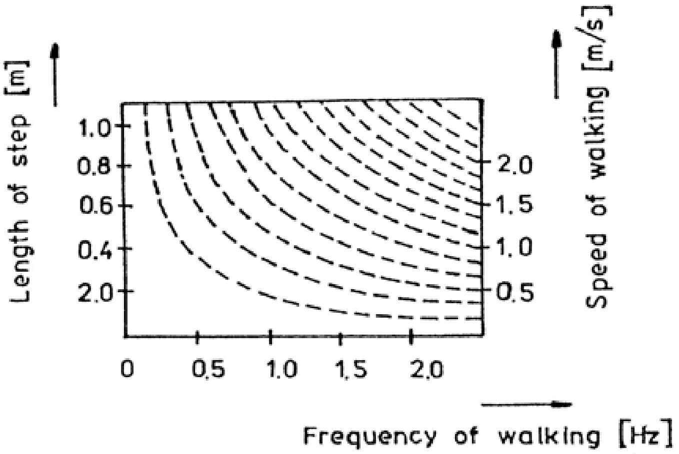

Fig. 2.8. A nomogram showing the dependence of the step length on the frequency and speed of walking (according to Shevchenko 1975).

Current research results allow conclusions to be drawn only for locomotion along a flat, horizontal and stiff surface. The effects of inclined and deformable surface. The effects of inclined and deformable surfaces upon the parameters of locomotion tracks have not yet been determined with any measure of accuracy and hence these tracks are amenable to analysis only at a very approximate level. As an example of this, a method of assessing the velocity of walking from the character of motion and the age of the individual will be presented.

The experimental basis of the analysis comprised 960 measurements of the necessary parameters of the individuals and of the corresponding patterns of locomotion and their tracks. These data were gathered and evaluated in cooperation with the Forensic Engineering of the Technical University in Brno.

Some of the kinematical parameters of walking – or of a single step as its element can be evaluated in relationship to the rhythm, or frequency, of the movement of locomotion (2Hz), and the minimum mechanical energy at a velocity of 4 km/hour (1.1 $m.s^{-1}$). Among these parameters, the following are the most prominent:

- the length of the step,
- the time sequence of the optimum step.

A linear dependence for both the length of the step and the frequency of walking on the overall velocity of the forward movement has been demonstrated to hold for normal, non-defective:

a) The length of the step

The characteristic relationships between the length of the step and the velocity of walking have been verified (e.g. Nyvlt (1979), Rocek (2005) with identical results. Any increases in the velocity of locomotion were effected uniformly by lengthening the step. According to experimental data, the step length of males of medium age (of body heights between 1.6 and 1.8 metres) was *(0.58—0.7)* m. Schevchenko (1975) sets the average length of the male step at approximately (0.7—0.8) m. Krylov et al. (1976) approximates the step length of a normally walking male of medium body build by the interval *(0.65—0.9)* m (and *(0.5—0.65)* m for females). The mean step length of *(0.75—0.8)* m for males and *(0.55—0.65)* m for females was proposed by Sapozhnikov (1940). Increases or decreases in the step length of about 0.1 m indicate modifications in the corresponding velocity of walking. Indoor's, the length of step tends to diminish. For common walking velocities (1.1 m s1), one step lasts about 0.68 seconds. In this interval the body is supported on either the right or the left foot for about 0.58 seconds, while the body is supported by both feet for only 0.1 seconds.

b) Time sequence of the step

For assessment of the optimum regime of walking, the time sequence of the individual step must also be considered. Above all, the duration's of the support and swinging phases of the step must be analyzed.

An analysis of the time sequence of the above defined principal phases of walking carried out for normal subjects having step lengths of 0.58 m and 0.64 m and for velocities of approximately 0.9 m.s$^{-1}$ and a corresponding frequency of walking of about 1.8 Hz revealed the following:

1. The duration of the support phase of one step (defined as the time interval between the first contact of one foot and the surface and removal of the other foot from the surface):

| | |
|---|---|
| $v$ = 0.9 (m.s$^{-1}$) | 400 ms, |
| $v$ = 1.1 (m.s$^{-1}$) | 338 ms. |

2. The duration of the swinging phase of one leg (defined as the time interval between the removal of a foot from the surface and its next contact with it)

| | |
|---|---|
| $v$ = 0.9 (m.s$^{-1}$) | 280 ms, |
| $v$ = 1.1 (m.s$^{-1}$) | 260 ms. |

3. The duration of a single step (defined as the length of the support and swinging phases of one leg)

| | |
|---|---|
| $v$ = 0.9 (m.s$^{-1}$) | 680 ms, |
| $v$ = 1.1 (m.s$^{-1}$) | 590 ms. |

These values are lower for defective individuals, but then also the velocity of their locomotion is lower. In general, in all cases studied, the duration's of the support and swinging phases of walking were observed to be inversely proportional to the speed of walking. In other words, at higher speeds, the lengths of both these intervals tend to decrease.

The speeds involved in ascending stairs range only between 39.5% and 51.2% of the speed of walking along a horizontal surface, while for descending the corresponding percentage has been ascertained to be 60.2%–64.1*%.* Technical Council Committee data (1976) are even more restricting: *35.7%*–40.7% for ascending, and 49.7*%–54.3*% for descending. For walking on inclined surfaces, on the other hand, the published data tend to show only modest reductions in the velocity of locomotion: *(5–10)* % for a gradient of 11.5*%,* and 25% for a 20% gradient. (* The same set of data has also been employed (Bombásek, Zoul 1982) as the experimental basis of a research study in the field of road safety, where the emphasis was placed on the means of analyzing the speed of walking of pedestrians with regard to the possibility of discovering the probable causes of accidents.). The objectivity of all consideration of the biomechanical content of criminalistic traces, and especially those concerning methods of assessing walking speeds of pedestrians, is greatly enhanced if other factors are accounted for, i.e. the sex of the individual in question, his or her age and physical fitness, health, motivation, the precise character of the surface along which the locomotion took place, to name only a few of the most obvious factors influencing the speed of walking.

Furthermore, sometimes the common subjective categories of the description of walking regarding its speed and general character must be worked with, in which case we usually talk of slow, normal, and fast walking, seen from the point of view of either the walking individual himself or an external observer. These measurements were performed for a fixed horizontal distance along a flat, rigid surface. The two basic categories of subjects, i.e. male and female, were further subdivided according to age into three groups: 15–30, 30–50, and 50–70 years of age. In each category, the speed of walking was determined, together with its description in terms of the above qualitative classification. The average value of the speed and its standard deviation were then computed for each subset of these data, and also a table of the corresponding relative frequencies was compiled. The results obtained are shown in summary form in Table 2.1.

Table 2.1. Summary of the results of measurements of the speed of walking.

| Character of the Gait | $m.s^{-1}$ | Group | | | | | |
|---|---|---|---|---|---|---|---|
| | | Males | | | Females | | |
| | | Age category (years of age) | | | Age category (years of age) | | |
| | | 15-30 | 30-50 | 50-70 | 15-30 | 30-50 | 50-70 |
| Slow | v | 1.16 | 1.09 | 0.98 | 1.07 | 1.03 | 0.99 |
| | $s_v$ | 0.19 | 0.16 | 0.13 | 0.14 | 0.13 | 0.16 |
| Standard | v | 1.52 | 1.39 | 1.17 | 1.38 | 1.22 | 1.02 |
| | $s_v$ | 0.20 | 0.15 | 0.13 | 0.14 | 0.16 | 0.12 |
| Fast | v | 1.74 | 1,65 | 1,52 | 1.59 | 1.46 | 1.30 |
| | $s_v$ | 0.12 | 0.14 | 0.21 | 0.15 | 0.14 | 0.19 |

v – The *average* velocity – sample mean value ($m.s^{-1}$)

$s_v$ – Standard deviation of the sample ($m.s^{-1}$)

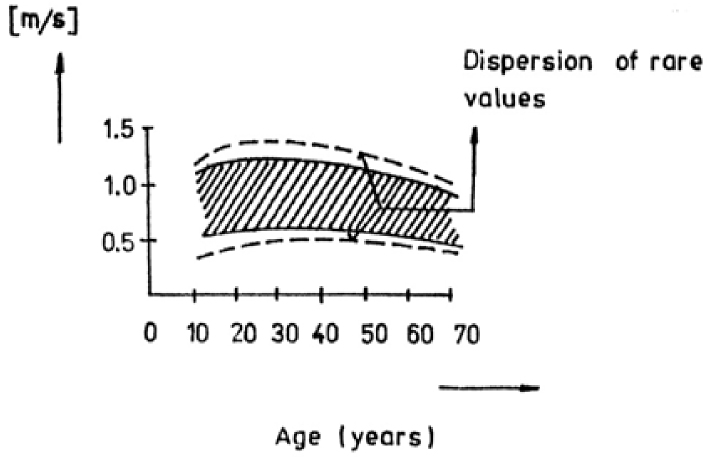

Fig. 2.9. Dependence of the speed of walking on the age of the subject, slow walking (Bombásek, Zoul 1982).

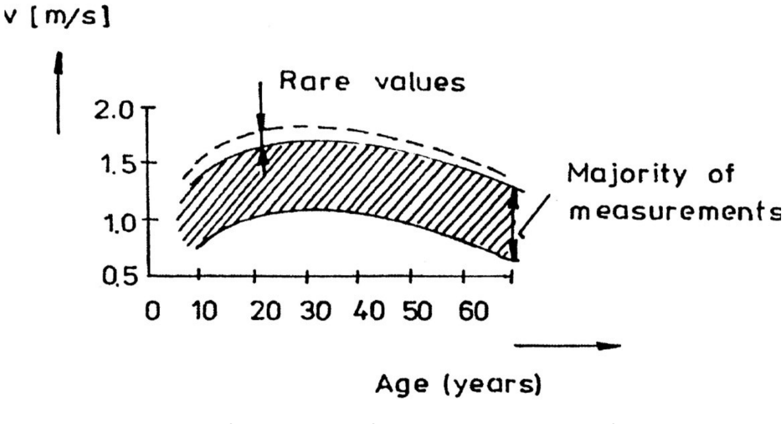

Fig. 2.10. Dependence of the speed of walking on the age of the subject, normal walking (Bombásek, Zoul 1982).

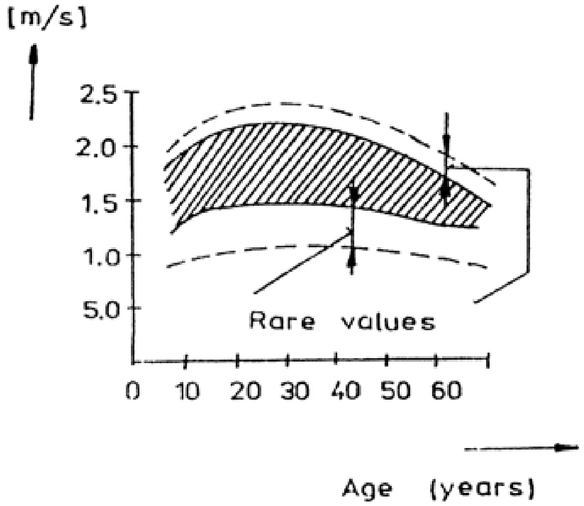

Fig. 2.11. Dependence of the speed of walking on the age of the subject, fast walking (Bombásek, Zoul 1982).

In comparing sample values of the mean speeds in mutually corresponding subsets of male and females with regard to age and the character of walking, only insignificant differences have been found. Therefore, further analysis of the experimental data was performed jointly for both subdivisions according to sex, the only remaining categories being those of age and character of walking. For possible comparison as well as for utilization in an analysis of sets of tracks encountered in criminalistic practice, diagrams showing the dependence of the speed of walking on its subjective character and the age of the pedestrian are presented here in Figs. 2.9, 2.10, 2.11.

### 2.6.3 Distribution of forces in human locomotion and their measurement

The theory of criminalistic analysis of tracks can be further extended to also cover features that reflect the various force interactions taking place at the moment of formation of the tracks. These are, for example, the depth of the imprints, the relative deformation of the surface in the central and boundary regions of the track, marked discontinuities in the track, caused by skidding, rolling, etc. No precise causal biomechanical correlation's between the forces deforming the surface receiving the imprint of the track and features detectable for this track are currently known with any measures of accuracy. The insufficient number of experiments that have been performed in the field, together with the currently existing level of theoretical understanding of the mechanisms of track imprinting, necessarily cause significant features of tracks to be neglected, which, in turn, decreases the amount of information derivable from such analyses with regard to individual attributes of the sought individual, including the patterns of his motorial behavior (Porada 1987).

For a deeper understanding of the mechanism involved in the formation of tracks of walking, the force interactions involved in the process must be thoroughly studied, since these indicate some of the most important subsets of identification features of track analysis.

From the point of view of biomechanics, the pattern of the reaction of the surface, reflecting the interaction of the foot with the ground, can be theoretically assumed to depend primarily on the shape of the foot, or shoe, on the configuration of the knee and hip joints, on the mechanical properties of the surface (e.g. earth), and on the force acting during the process.

Since the part of the foot to come into contact with the surface is three-dimensional, and has a shape that is too complex to permit any attempts at mathematical definition, the distribution of the force field acting upon the surface is non-homogeneous. The forces observed are moreover dependent on time within each specific phase of the contact.

The utmost precision in the of processes of modeling and permanent recording of the shape of the track is necessary for any further analysis to proceed,

which is aimed at solving the following tasks:

- evaluation of the action forces involved, together with their distribution;
- assessment of the deformation energy necessary for the formation of the entire track or part of it;
- appraisal of the individual configuration of the lower limb;
- establishment of correlation’s between attributes of the locomotion and the observed deforming effects of the action forces with regard to various surfaces etc.

The considerable theoretical and technical demands of such investigations have caused current efforts to be aimed at the acquisition of basic methodological experience regarding the means of modeling the surface reaction, together with only the most fundamental techniques of its assessment.

### 2.6.4 Action forces for rigid surfaces

Many authors have treated the problem of the dynamics of locomotion along rigid surfaces. Among the available sources of information, the works of Ratov (1976) and Cappozzo, Leo, and Pedotti (1975) should be named as the ones providing the most valuable indications of the current trends in the application of complex computing techniques for kinematic and dynamic analyses of tracks. Cavanagh and Lafortune [26] treated the problem of dynamic modeling of surface response, including the shape of the time dependence of the vectors of the resulting action forces and the dynamics of the point of application of these forces. Draganich et al. (1980) presented their results obtained from electron measurements of the instant contact area between the sole of the foot and the surface.

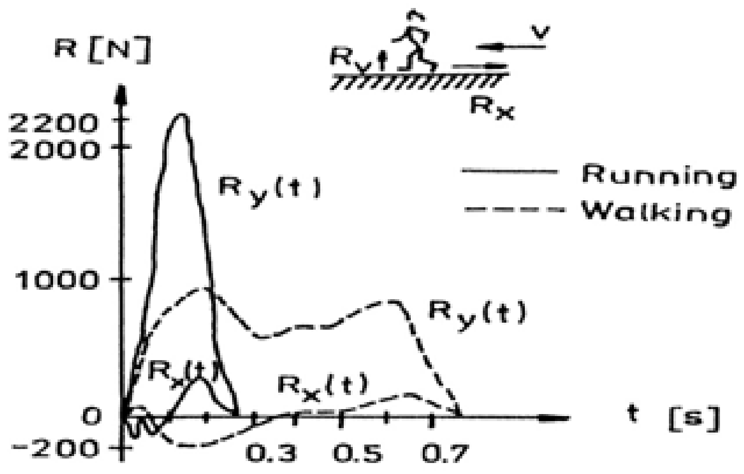

Fig. 2.12. A dynamographic recording of the shape of the dependence of the reaction forces on time for walking and running.

The action forces involved in the contact between the foot and the surface cause surface reactions opposite to them which, in their turn, as external forces make human locomotion possible. The differences in the basic modes of locomotion can be assessed from various points of view, but they can be identified with a relatively high degree of accuracy by analyzing the dynamographic model of the surface reaction, from which the specific mode of locomotion can be reliably determined, i.e. we can distinguish between walking and running on the basis of the model alone.

The shape of the time dependence of the reaction components $R_x(t)$ and $R_y(t)$ is shown in Fig. 2.12 for the walking of a normal, healthy subject. The shape of $R_y(t)$ is characterized by its double-peaked curve with two local maxima and one local minimum. For the shape of the dynamogram for running shown in the same figure and for the corresponding course of $R_y(t)$, a curve with only one peak is typical. The dynamographical recording of the course of the reaction forces shown in Fig. 2.12 for walking (v = 2.2 $m.s^{-1}$) and for running (*v* = 8.3 $m.s^{-1}$) was obtained for a subject with a body mass of 69.4 kg.

The first of the two following examples deals with a combined method of kinematical/dynamographical measurement capable of revealing possible changes in the trends of the individual components of the action forces (in detail, see Karas, Porada 1977, Porada 1977). The second example shows a method of measuring action forces for deformable surfaces in dispersive environments.

## 2.6.5 Methods of measuring action forces on rigid surfaces

The experimental subject moved with varying speed, in all cases with natural frequencies of walking and lengths of step. In each case, the changes in the action forces of walking and running were recorded. The results thus obtained are shown in Figs. 2.13, 2.14, in which the trends of the individual components of the action forces are plotted for each experimental frequency. The double-peaked character of the vertical component of the action force, $F_{Ry}(t)$ of walking is quite apparent here. The plot of $F_{Ry}(t)$ for running is typically a curve with only one peak.

Contrary to walking, the vertical component of the reaction force for running does not tend exhibit any significant local minimum in its curve. This indicates that, until the moment of the interaction, at which the vertical component of the reaction force reaches its maximum, the centre of gravity of the body is lowered. At the moment of local maximum of the corresponding curve, the centre of gravity reaches its lowest level. The interaction with the surface is accompainied by gradual flexion of the knee joint, taking place until the reaction reaches a maximum.

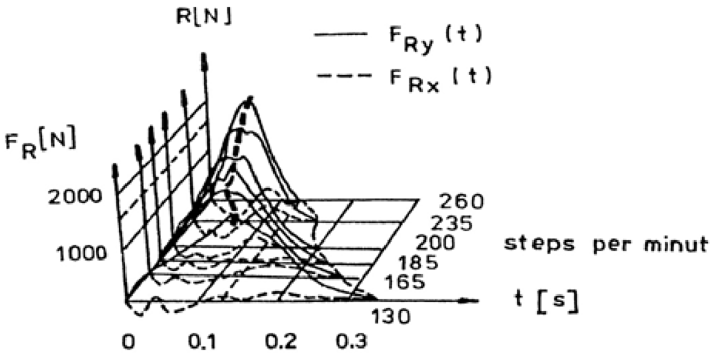

Fig. 2.13. Trends with time of components of the action force for several frequencies of walking. Frequencies are given in steps per minute.

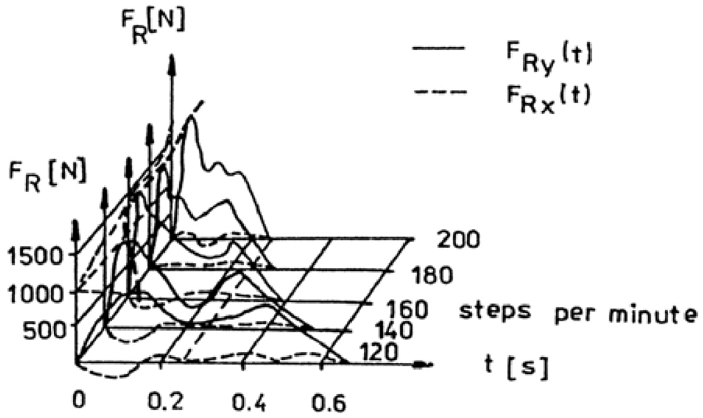

Fig. 2.14. Trends with time of components of the action force for running. Frequencies in steps per minute.

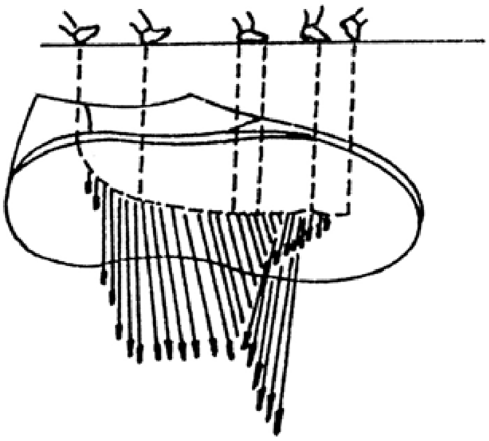

Fig. 2.15. An example of the development with time of the action force during the interaction between a shoe and a rigid surface. The points of application, direction, sense, and magnitude of the vector of the action force were recorded by means of a Kistler piezoelectric measuring platform.

For illustration, a schematic representation of the dynamics of the action forces during the interaction between a shoe and a surface is shown in Fig. 2.15. The gradual change of the point of application of the action force on the sole of the shoe, dependent on the distinct phases of the support stage, is apparent from the figure. In a similar way, the direction and magnitude of the vector of the action force can also be expressed.

Both the results of measurements and common sense indicate the same conclusion: with increasing frequency of walking, the duration of the interaction between the foot and the surface shortens. The time needed for the vertical component of the reaction force to reach a maximum also decreases, and the magnitude of this maximum value increases. Further increases in step frequency lead the subject up to the “critical limit” of walking, beyond which the flight phase actually occurs and walking changes into running.

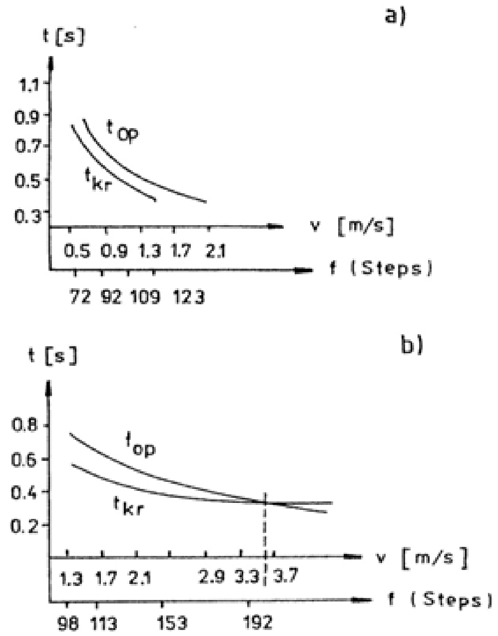

Fig. 2.16. Diagrams showing the dependence of the duration of the support phase, $t_{sp}$, of the foot/surface interaction and the duration of the step, $t_{st}$, on the speed or frequency of walking.

Diagrams reflecting the dependence of the duration of the support phase, $t_{sp}$, of the foot/surface interaction for walking and of the duration of the entire step, $t_{st}$, on the speed of walking have been compiled from experimental data on the time sequence of the motion (Fig. 2.16 a, b). The intersection of the curves corresponding to $t_{sp}$ and $t_{st}$ represents the critical point at which the character of the locomotion of the studied subject changes qualitatively. It follows that for speeds higher than that at which the critical point is reached, walking permanently transforms into running with a flight phase.

### 2.6.6 Measurements of action forces for deformable surfaces in dispersive environments

Until now, all available studies concerned with appraisal of the magnitude of the action forces have accounted exclusively for locomotion along rigid surfaces. Any further progress in the criminalistic theory of tracks as well as its practical applicability is necessarily bound to the possibility of assessing the magnitudes of the action forces for locomotion along deformable surfaces, such as cohesive soils. Our experimental evaluation of the forces used a steel frame, about *5* cm deep, the circumference of which overlapped the contour of the measuring pad. The frame was filled with wet sand with a consistency modified so as to simulate commonly encountered conditions. A wood platform along the path of the subject across the measuring pad compensated for any differences in the horizontal levels, thus preventing any disruption to the normal motorial pattern of walking. Fig. 2.17 shows the dynamographical recording of the vertical component of the reaction force $F_{Rx}$ for walking on simulated soil, in which the impulses of the accelerating forces have been marked. With the assumption of fixed boundary conditions, i.e. of the vertical component of the velocity of the centre of gravity of the whole body, of the dependence of the vertical changes in the level of the centre of gravity on time can be computed in terms of these impulses. The body mass of the experimental subject was 68.2 kg and the speed of walking was 4.1 m.s$^{-1}$.

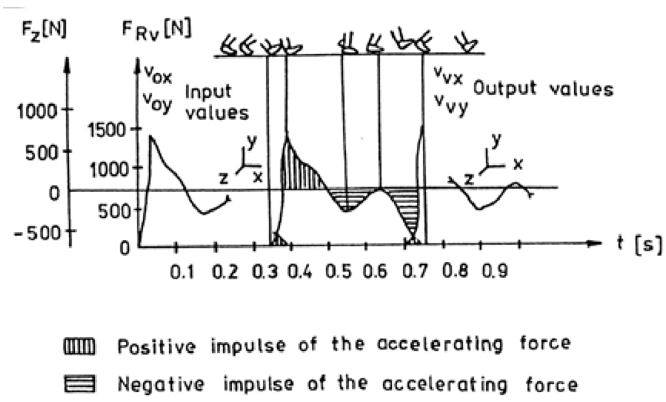

Fig. 2.17. A dynamographic recording of the vertical component of the reaction force, $F_{ry}$, for fast walking on a model soil (wet sand) in which the impulses of the accelerating forces are indicated by the shadowed areas.

Fig. 2.18 shows a dynamographical recording of the horizontal component of the reaction force, $F_{Rx}$, for the same experimental subject, walking on soil, with an indication of the impulses of the accelerating force in the horizontal direction. Again, from knowledge of the boundary conditions of the analysis, i.e. of the horizontal component of the velocity of the centre of gravity of the whole body, the functional dependence of the horizontal changes in the location of the centre of gravity of the body during locomotion can be determined.

To a first approximation, the dynamograms obtained for three surfaces of different rigidities (artificial track surface, wet sand, and an ideally rigid surface) revealed the following fundamental insights:

1. All dynamographical curves of walking retain their typical double-peaked pattern.
2. The individual dynamograrns displayed a certain shift for each of the surfaces, such that lower values of the vector components of the reaction forces were reached in the local maximums and minimums for more easily deformable surfaces. This shift in the magnitude of the vector of force to lower values was, in the case of wet sand, about 150 N in comparison with the value for an ideally rigid surface. This decrease (in absolute values from 1550 N to 1400 N) was apparently caused by dissipation of the vertical component of the action force by plastic deformation of the yielding surface.

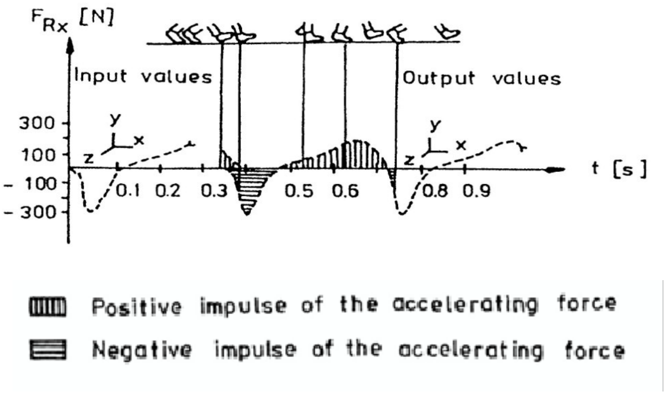

Fig. 2.18. A dynamographic recording of the horizontal component of the reaction force, $F_{Rx}$, for fast walking on a model soil (wet sand) showing the impulses of the accelerating force in the horizontal direction.

Although this difference in the magnitudes of the vertical forces acting of surfaces of differing rigidities appears only modest, all further analyses of tracks with regard to the forces involved will require proper definition of the relationship describing the deformability of the individual types of soil and their physical properties, such as specific mass, porosity, active surface, thermal conductivity etc.

Further experiments will be required, not only for surfaces with different physical properties but also to cover the range of possible speeds of locomotion and slopes of the surface.

In summary:

The dynamograms obtained experimentally for the locomotion of a subject involving walking, running, or jumping on a force-measurement pad lead us to conclude that:

- the individual's anatomy and the structure of the dynamic stereotype of walking or running at a constant speed apparently cause each individual to have his or her more or less characteristic surface-reaction pattern (dynamogram);
- the mode of locomotion (walking or running) can by reliably deduced from the dynamogram;
- for walking or running at a constant speed, the dynamographic recording can serve as basis for a reasonable firm identification of an individual;
- the shape of the dependence of the surface reaction on time is, for both walking and running, greatly influenced by changes in the velocity of locomotion and the manner of carrying any load (in either of the hands, on the back etc);
- the shapes of the dynamograms for surfaces other than ideally rigid, such as soil, sand, and possibly also in various mixtures with clay, slag, etc., will be different in each particular case and no closer estimation of its character can be made unless further experiments are performed.

All previous experiments, having been performed by either measurement of the pressures in the soil under the impact of feet (or of the corresponding forces) by a platform of the form described above or by application of photogrammetric techniques for analysis of plastic tracks, have proved the high theoretical and technical demands of these procedures. This approach, however, represents a potential source of improvement in our understanding of the mechanisms involved in the formation of criminalistic tracks (Fig. 2.5) and of the current methods of their analysis, which can ultimately solve the problem of identifying a criminal by his tracks. A promising combination of this kind is represented by the joint use of methods that record the surface reaction by means of the force-measuring platform – by means of which the dependence of the resulting reaction force of the surface on time, or on the phase of the step, can be obtained – and photogrammetrie analysis of the surface deformation, which again yield results describing the distribution of forces, helpful for understanding the morphology of plastic tracks of humans (Figs. 2.19, 2.20).

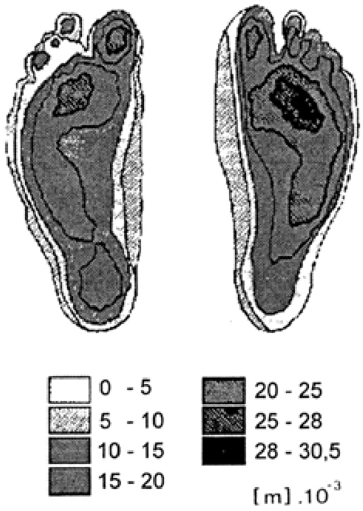

Fig. 2.19. A re-drawn and modified stereoscopic image of a plastic track. The plastic track was formed by imprinting the feet of a subject, standing motionless, into sculptor's clay. The real vertical differences were 2.5 mm for standards 0-25, 1.5 mm for standards 25-28, and 1.25 mm for standards 28-30.5. The values indicated by the figure, i.e. twice as large, were used in order to improve the accuracy of evaluation of the image.

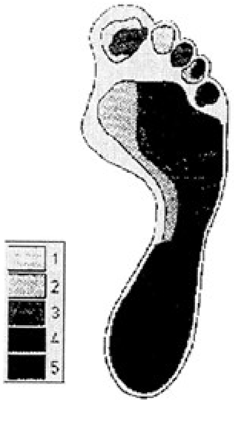

Fig. 2.20. A drawing showing the pressure distribution under the right foot of a subject standing motionless on a stiff surface. The drawing is based on visual estimation of areas of equal density shown by a photograph of a planar track. The differently coloured areas correspond to different ranges of pressure of the foot/surface interaction; the pressure grows with the increasing index of the colour pattern.

## 2.7 Some theoretical aspects of the identification of a criminal by his tracks in a dispersive environment

As far as it is known to the authors, no detailed study of the correlation between the body mass of a criminal and the states of stress and consequent deformation of soils has appeared in foreign or Czechoslovak literature to date. Also the analysis of the state of stress itself, essential for the development of suitable stress gauges, remains to be tackled. It follows that no methods of fast and reliable prediction of the body mass of a criminal based on analysis of his tracks have yet been developed or utilized in practice. Although several studies have appeared in the field recently (Porada 1977, 1978, 1985, 1987), their interest in the area described above is only marginal.

Soils in general are dispersive materials, consisting, under normal conditions, of mineral components comprising the matrix of the material, water, gases, and when the temperature is below the freezing point of water, another solid component, ice. Each of these components contributes specifically to the state of deformation of the soil under mechanical loading. The term deformation of dispersive environment is used to mean any change in the shape of the material caused by either external forces, such as inertial effects, temperature changes, or external humidity, or any other factors. The process of the development of deformation with time is a very complex phenomenon. During a relatively long time interval covering the entire duration of the effects of the external factors not only does re-location of individual components take place in the dispersive material but also these components undergo qualitative changes in themselves. The situation is complicated, amongst other factors, by the evaporation of a certain amount of water from porous soils; it follows that the longer the time interval between origination and analysis of a track, the greater the potential error. These discrepancies are mainly caused by inaccuracies in the assessment of some of the principal material parameters of the studied environment, such as its deformation modulus.

The extent of the deformation at the moment of formation of a track depends on the degree to which the dispersive material is saturated with water. For this purpose, experiments have been performed for specimens of clay, which disclosed that, for example, a 3.5% decrease in the degree of water saturation of the soil decreases the pressure of the water by a factor of three, while for a 5% decrease the pressure decreases four times. The implications of these observations will be explained later.

Soil deforms almost exclusively by compression of its pores, while, at the same time, a certain amount of re-structuring of the mineral components occurs, in the course of which some of the material particles are crushed. Modeling of the process of formation of new structures has so far been extremely difficult. It is currently becoming apparent that for further progress to be made the use of stochastic models will be indispensable, since the overall process comprises not only the crushing of a certain proportion of the material particles but also their elastic and non-elastic deformations.

If the proportion of gases is sufficiently high and the water contained in the pores does not constitute a hydraulically continuous phase, and, moreover, no additional re-location of the components during the compression of the entire structure takes place, the global deformation of the structure can be described according to the laws of continuum mechanics. There can be no doubt that a closer approximation is achieved by modeling the interactions of all three components of the material, but the respective regions of applicability of the simplified and of the more complex models have not been clearly defined yet and further research in the area is necessary.

### 2.7.1 Simulation of a track by means of equivalent loading

One feasible method of practical appraisal of the deformability of a specific surface by the vertical and horizontal forces involved in the interaction in the support phase of walking is represented by simulation of the criminal's track by the use of equivalent loading of the soil in the vicinity of the original track. The method is based on the following concept: the track left by the criminal would be cast in a suitable material that has sufficient mechanical strength after solidification. From the formula for the length of the support phase of walking and from the known speed of walking, the relative time distribution of the individual local maxima and minima of both the vertical and horizontal forces can be determined, bearing in mind that the latter force acts in the forward direction during the first half of the support phase and backwards in the second. A comparative imprint of the casting of the criminal's track is then made by means of a suitable loading device (e.g. a hydraulic one) in the soil near the original track. The loading force of the device must be adjusted so as to achieve the closest possible correspondence between the original and artificial tracks, conceivably by a process of trial and error. Once identity between the original track and its model has been achieved, the values of the above mentioned local maxima and minima of the vertical and horizontal forces can be determined, and on the basis of these, the mass of the criminal can be evaluated from the diagrams published in reference (Karas, Porada 1978 for five different walking speeds ranging between *0.5* and 2.5 m/s). The estimated value of the body mass would then be the average of these five estimations.

For the practical application of this method, a suitable measuring and loading device would have to be designed and manufactured, and also the choice of the material for casting the track would be crucial, as it must be of sufficient mechanical strength and must also be capable of being properly locked into the loading device. The entire system requires testing under field conditions, which will serve both to determine any modifications to the proposed procedure and verify the method.

An example of a simplified measuring device with a circular loading plate is shown in Fig. 2.21. The device is capable of a compressive effect only in the vertical direction. For improved accuracy of the simulation, a device capable of exerting both vertical and horizontal forces must be designed. The forces involved in the application of the method of equivalent loading must be controlled according to their variation with time – see, for example, the dynamograms shown in Fig. 2.27. The locking system of the measuring head must therefore be designed so as to allow the impacting angle of the model to be varied according to a defined pattern derived from the time sequence of the phases of the support stage of walking (Porada 1987).

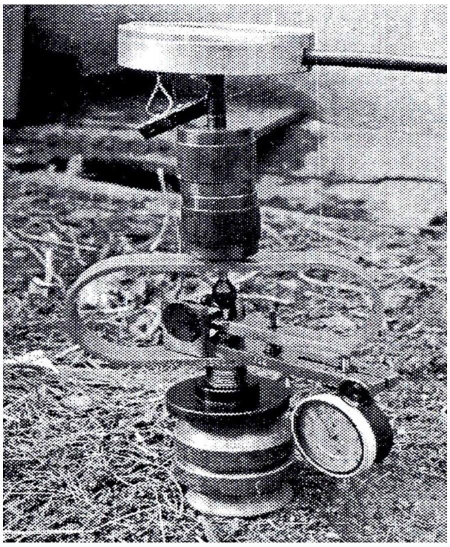

Fig. 2.21. A conceptual proposition of a simplified load-measuring device for field work (Porada 1987).

## 2.7.2 Evaluation of the overall compression by means of the compression coefficient

The compression of homogeneous or layered soils, *s,* can be evaluated using a relationship given by Myslivec and Kysela (1975), according to Terzaghi and Buisman, as

$$s = \int_0^{h_i} \frac{2.3}{C} \log\left(1+\frac{\Delta\sigma_2}{\sigma_2}\right) dh = \sum_{k\acute{e}1}^{n} \frac{h_k}{C_k} 2.3 \log\left(1+\frac{\Delta\sigma_2}{\sigma_2}\right),$$

where $\sum_{k=1}^{n} h_k = h_i$ and the numerical values of the constants of the individual layers, $C_k$, can be different. This relationship cannot be used for soils with a non-stable volume.

With regard to the loading force, corresponding in this case to the weight of the individual, G, and the deformation of the soil caused by this force, in criminalistic analysis of tracks *n* = 1. The above equation will then take the form

$$s = \frac{h}{C} 2.3. \log. \left(1+\frac{\Delta\sigma_2}{\sigma_2}\right)$$

The original average vertical stress present in the central plane of each of the layers prior to formation of the track is represented by u. The increment in the vertical stress, $\Delta\sigma_2$, originating in the central plane of the layer, owing to the loading force of the body weight of the subject is, as a rule, determined from the theory of an elastic semiinfinite continuum, which is applicable in practice to homogeneous soils of depths at least two and half times the width of the track.

Since the largest increments in the vertical stress, $\Delta\sigma_2$, occur immediately below the track, this is also the location of the most intensive compression. This depth is usually denoted as the effective depth, or the active one, the extent of which is dependent on the load applied, the compressibility of the soil, and the area of the track. For ordinary analyses of the overall compression, the soil compressibility needs to be considered only to a depth equal to twice the average width of the track B.

Both the vertical stress, $\sigma_2$, and its increment, $\Delta\sigma_2$, must be evaluated under the characteristic point of the track, which is defined as the point of intersection of lines parallel to the axes of the track running at distances from the centre of the track equal to 0.37 B and 0.37 *L,* where *B* and *L* are the width and length of the track respectively. For the current purpose, the track can be considered to be represented by a rectangle of sides Land *B,* where *B* is taken as the average of the widths of the track in the areas of the sole and the heel (Fig. 2.22).

As neither the location and time nor other circumstances of a criminal act can be foretold, the coefficients of compressibility cannot be evaluated beforehand under laboratory conditions in order to observe the rule of the analysis requiring integrity of the sample. Hence the necessity directly follows for sampling the soil in the immediate vicinity of the track, which procedure must not affect the integrity of the track itself, but, at the same time, samples of soil homogeneous with that deformed in the track must be obtained in order to achieve adequacy of the physical properties of the two.

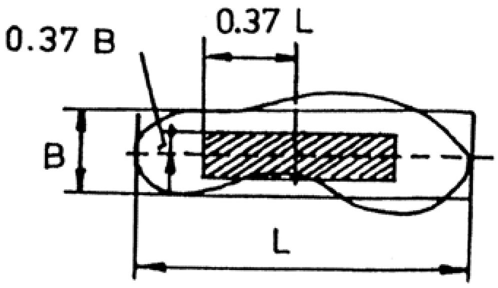

Fig. 2.22. Geometric analysis of a track for evaluation of the overall compression. (The values 0.37 B and 0.37 L have been determined empirically.)

The average magnitude of the stress under the area limited by the area limited by the contour of the track has been taken as that of the characteristic points and therefore the compression is evaluated on a vertical line passing through one of these points. For the analysis of a standing subject, the overall compression will also have to be evaluated by use of the deformability moduli $E_0$ and $M_0$.

The situation is much more involved for a moving subject since, in this case, the direction and magnitude, and the point of application of the loading forces change with time. The current assessment procedures consider only the compression owing to the increment in the vertical stress, $\Delta\sigma_2$, while the components of the stress increment in the horizontal plane, causing compression of the soil at the sides of the track, are neglected. These effects can be disregarded for practical purposes since their presence becomes marked only at very high stresses. The depth of compression has not been observed to be significantly affected by these effects within the whole range of loading due to the weight of the subject, G, and the corresponding inertial force, *D.*

Also the impact of the load increment in the horizontal plane in cases of combined vertical compression and lateral extrusion of the soil in the vicinity of the track as for marshy soils has been neglected (Porada 1987).

### 2.7.3 The balance of forces and energy during locomotion

The existing balance of forces and energy during locomotion or, more specifically, for walking, must be clearly understood for any further study of the mechanisms involved in the formation of tracks, as it focuses the subsequent analysis onto a significant set of characteristic features of the track (Karas, Porada 1978).

a) Balance of energy and external mechanical work during walking.

The anatomy of the human apparatus of locomotion leads to changes in the potential energy, $E_P$, of the body during walking in relation to the phase of the step. The velocities of the forward movement and the vertical movement of the centre of gravity are reflected in the kinetic energies $E_h$ and $E_v$, respectively. The global level of the mechanical energy of the centre of gravity, *E,* is, at each instant, given as the sum of these energies:

$$E = E_P + E_h + E_v = Gh + \frac{1}{2}mv_h^2 + \frac{1}{2}mv_v^2 \quad ,$$

The mechanical work done by the muscles involved in effecting movement in individual joints can be determined for each instant of the movement by means of the equation

$$W_{ij} = \frac{1}{2}\left(M_{ij} + M_{ij+1}\right)\left(\eta_{ij+1} - \eta_{ij}\right)$$

where $W_{ij}$ is the work performed on the joint *i* during the j-th time interval; $\eta$ denotes the degree of rotation between the adjoining segments.

Note: To solve Eqn., the moments of the forces of the muscles involved, $M_i$, which govern the motions of the ankle, knee, and hip joints, would have to be assessed first, as presented by Cappozzo (1976).

The instantaneous energy of the i-th body segment is then given by

$$E_i = G_i s_i + \frac{1}{2}mv_i^2 + \frac{1}{2}J_i\omega_i^2$$

in which $G_i$ represents the force of gravity, $s_i$ is the height of the centre of gravity of the segment above the reference plane, $m_i$, $v_i$ and $J_i$ are the mass, velocity of the centre of gravity, and moment of inertia relative to the centre of gravity of the segment respectively, and $\omega_1$ stands for its angular velocity.

Note: These kinematic data could serve as the basis for assessing the energies of the individual body segments and of the overall energy of the moving body given by the sum of these.

However, evaluation of the external work done by the muscles according to is of only marginal importance. Evaluation of the actual overall work done by the muscles, including its internal components, among the outer effects of which the external work performed at the segment must be also counted, has proved to be a difficult theoretical problem the solution of which is going to require, at the very least, a number of complex experiments. The intrinsic complexity of the process of assessing the internal work done by the muscles follows from the fact that this work comprises both the work performed by a muscle during its concurrent contraction and elongation the so-called negative work and the work performed during isometric contraction. For our purposes, however, the approximate value of the work done by the muscle given by Eqn. will be sufficient.

The change in the potential energy, $E_p$, and the kinetic energies, $E_h$, $E_v$, are out of phase for walking, similar to the situation observed for a rolling egg Fenn (1930). On the other hand, they are in phase for running, in a pattern similar to that observed for a bouncing ball. All the individual energy compoments must be covered by the mechanical work exerted during walking. This work is partially recovered and alleviates the particular phase of walking and is partially lost, for example, by deformation of the surface, etc. The limited ability of the human body to cover this work by muscle activation of the body parts involved in locomotion also limits the velocity of the forward motion.

The change in the potential energy of the centre of gravity and that in the energy corresponding to the forward movement are, for walking, virtually of opposite phase. Hence each step must be accompanied by activation of muscles of locomotion, by which the “rolling of the egg” is preserved. These muscles perform in each step the so-called external positive work. The increments in the kinetic energies of the vertical movement of the centre of gravity and of the forward movement can be considered to be the effects of the corresponding work done by the muscles.

The external positive work, $W_{ext}$, which represents the external effect of the activity of the muscles of locomotion, is an important indicator of the degree of activation of these muscles. This level of activation increases when the force of gravity decreases its contribution to the forward motion in the individual phases of the step, or even impedes the motion.

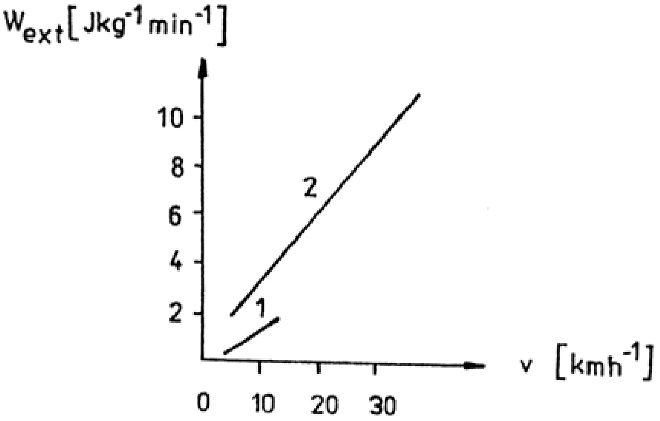

Fig. 2.23. The dependence of the specific positive external work. $W_{ext}$, expressed for one kilogram of body mass and one minute of motion, on the speed of locomotion, v. *1* – walking, *2* – running (modified, according to Cavagna 1975).

Experiments performed with a force-measuring platform of dimensions 4 by *0.5* metres, equipped with both vertical and horizontal gauges, and for which the forward velocity was measured by means of a photo-electric cell, the data being recorded on a multitrack tape recorder Porada (1977), Karas (1978) carried out for 10 healthy subjects of medium age have shown the following:

1. The external positive work related to one kilogram of body mass and one minute of motion does not increase linearly with the forward speed of locomotion for walking. The increase in $W_{ext}$, for running, which represents a mode of locomotion with a different mechanism, is linear and is shifted towards higher values of energy – see Fig. 2.23.
2. The minimum energy supply for walking, related to one kilogram of body mass and one kilometre of distance covered, is reached for velocities around 4 km/hour. As seen from Fig. 2.24, the value of this parameter rises at both sides of this local extreme.
3. The degree of recovery of the mechanical energy in walking is dependent on the forward speed of the motion, and for running almost no recovery takes place since no conversion of potential energy, $E_p$, into kinetic energy, $E_h$, is possible, and vice versa. The recovery of energy for walking as much as 65% for speeds between 4 and 5 km/hour, while for running this value ranges only between 0 and 4%.

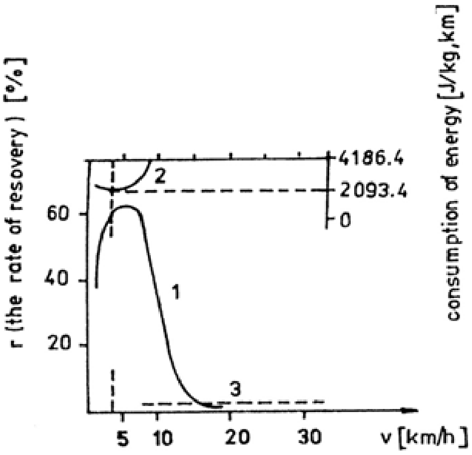

Fig. 2.24. Variability of the rate of recovery of mechanical energy for walking, curve *1.* and running, curve *3,* expressed as percentage of the energy corresponding to the vertical and horizontal motion of the centre of gravity of the body. The curve 2 shows the dependence of velocity of the consumption of energy expressed for one kilogram of body mass and one kilometre of distance – the upper right – hand side scale. (According to Cavagna (1976), modified.)

b) Balance of the energy of walking.

As Eqn. shows, the instantaneous levels of the mechanical energy of an arbitrary body segment or of the body as a whole can be analytically assessed. Such an analysis, however, requires the necessary input data to be known. The currently available state of the art experimental devices are capable of providing these data. These basic data follow from kinematical analyses of walking on the one hand and from analyses of data acquired by dynamographical techniques on the other, the latter methods being aimed specifically at methods of recording and analyzing the responses of the surfaces of contact. These painstaking procedures have been partially or fully automated. Fig. 2.25 presents an example of the pattern of the dependence of the instantaneous levels of the mechanical energy of walking on time. The relationships provided by the figure show the flow of mechanical energies for walking at a frequency around 2 Hz, corresponding to a speed of a normal subject of about 4 km/hour. The positive external work required in this case is the lowest, hence the frequency of 2 Hz is that preferred by humans in their choice of the rhythm of motions of locomotion (not only in walking but also in skipping, trotting, or dancing), since by this choice, the innate time pattern of the contractive muscular reflexes is optimally respected (Hasse 1976).

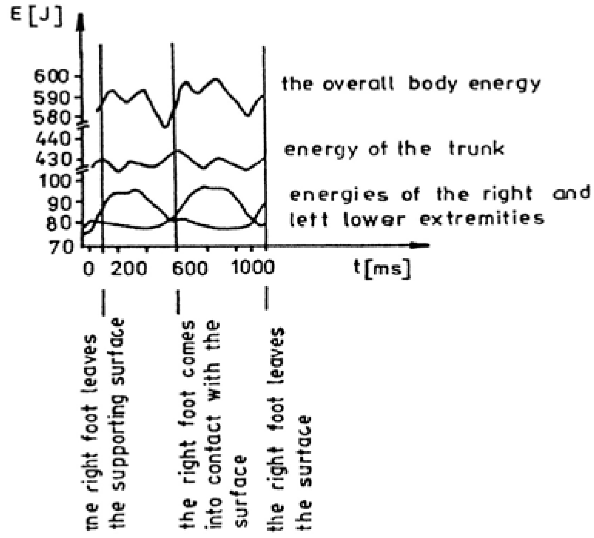

Fig. 2.25. An example of the values of the instant energies, E, and of the overall energy of the body. The dependence on time is shown for two consequent walking steps with a frequency of about 2 Hz (according to David (1976), modified).

The brief analysis of balance of the energy and mechanical work of walking indicates their variability with the individual phases of the motion (Fig. 2.26). It can be further inferred that the magnitude of the external positive muscle work exerted tends to increase with increasing speed of the motion and that the degree of mechanical energy recovered, by which the forward motion is maintained, decreases with increasing speed. This analysis alone leads us to assume that this variability will tend to be reflected also in the shape of the time dependence of the action forces involved in the interaction between the foot and the surface. The most convenient experimental procedure for assessing the action forces together with an analysis of the complex deformation processes occurring at the surface is that of recording the response of the platform and subsequent comparison of the prominent features of the track and the recorded pattern of the action forces. It maybe expedient to reiterate that both the process of deformation and the ultimate shape of the track will also be functions of the material properties of the surface.

c) The forces acting on the surface.

The action forces at the contact between the foot and the surface give rise to surface reactions with identical magnitudes but opposite directions, which, in their turn, as external forces, make locomotion possible. The presently available experimental equipment allows two different phenomena to be measured:

1. The resulting action force or the reaction to it can be measured by a force platform in the vertical, frontal, and transverse directions, and the corresponding axes are usually denoted as *Y* X, and *Z* respectively.

2. The elementary action or reaction forces can be measured in only the vertical direction using a pressure measuring device.

The quantitative analysis of the photographic recordings of the force distribution as acquired using such experimental equipment still remains to be tackled. Visual appraisal of individual photographs, or of sequences of them, so far remains the only analytical method available. However, the currently available sophisticated technology of the hardware systems of force-measuring platforms is capable of providing accurate measurements of the resulting action force, or of the reaction. All previous experiments have shown that the reaction patterns of rigid surfaces differ considerably from case to case and also that some of the characteristic individual features of locomotion are reflected in the reaction pattern to the extent that clear distinctions can be made between walking and running etc. (Karas, Porada 1977.)

The experimental work done by Andriacchi [43] can be utilized for further study of the mutual correlation between the components of the resulting action force in the directions X, Y and Z and the precise form of the track. These data were obtained by experiments on 17 normal subjects aged between 22 and 59 years with weights in the range (436−1 050) N and heights in the range *(155–180)* cm. On the basis of the published numerical data, diagrams were obtained in a form likely to be suitable for future analytical studies of tracks. Transverse action forces are omitted from further studies, since their significance in the analysis of tracks for criminalistic purposes is negligible.

The diagrams shown in Figs. 2.26, 2.27, 2.28, 2.29, 2.30, 2.31, 2.32 can be used to infer the following basic observations:

- The trends of the relationships $A_x(t)$, $A_y(t)$ have common characteristics for each recorded case of walking of normal healthy subjects; i.e. two local maxima. $Y_1$, $Y_3$, and one local minimum, $Y_2$, of the latter component, changing sense of the $A_x$ component with two charactertistic extremes $X_2$, $X_3$.

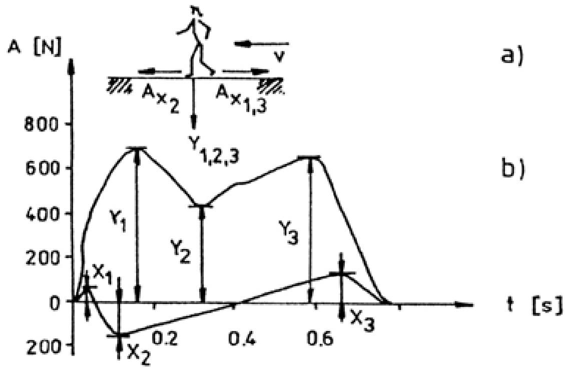

Fig. 2.26. a) Orientation of the action forces, $A_{x,y}$ during their action upon the surface in various phases of the contact between the foot and the surface. b) An example of the dependence on time, t, of the action forces, *A,* during the contact between the foot and the surface, showing the three characteristic amplitudes in the vertical direction, $Y_{123}$.

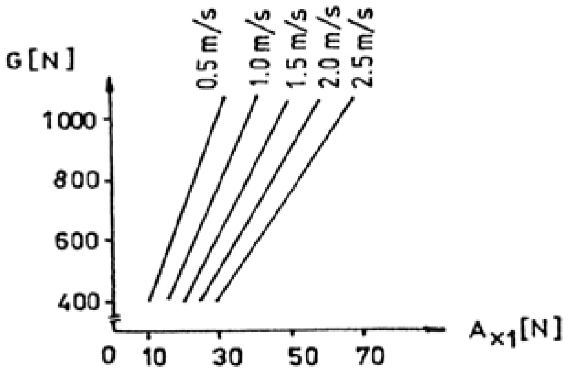

Fig. 2.27. The relationship between the frontal action force $A_{x1}$ acting in the initial phase of the foot/surface interaction in the backward direction and the force due to gravity on the body, shown here for several speeds of walking. The ± 45 % scatter from the linear regression shown, at a *5%* significance level, severely restricts any practical applications of the graphs.

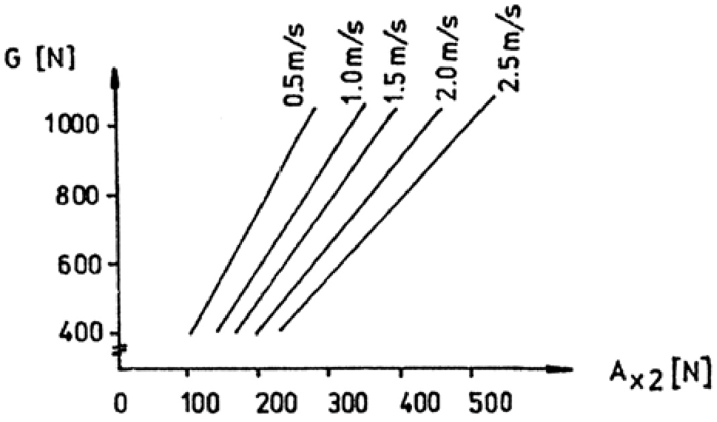

Fig. 2.28. The relationship between the frontal action force $A_{x2}$, and the force due to gravity. G, in the initial phase of the contact, shown for several speeds of walking. The orientation of this component is forwards, and ± *7.5*% scatter, at *5*% significance level, from the linear regressions shown has been obtained.

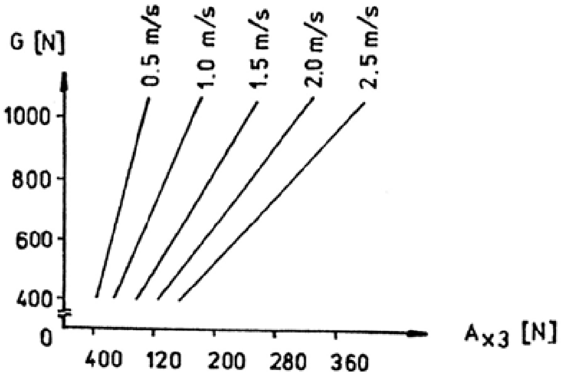

Fig. 2.29. The relationship between the frontal action force $A_{x3}$, of the final phase of the contact and the force due to gravity, G, for several speeds of walking. $A_{x3}$ acts backwards it represents the propelling force of the back foot – and a 7.6% scatter, at a 5% significance level, from the linear regression has been observed.

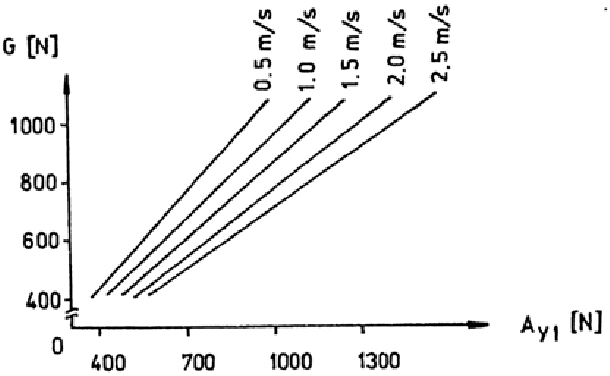

Fig. 2.30. The relationship between the vertical action force $A_{y1}$ of the foot, surface interaction and the force due to gravity. G. for several speeds of walking (± 7.5% scatter from the linear regression at the 5% significance level).

- The agreement of the assumed linear relationships between the force of gravity, G, and the resulting action forces in the forward and vertical directions, $A_{x123}$, $A_{y123}$, respectively, is surprisingly good for all the individual walking speeds (0.5–2.5) m.s$^{-1}$, which is (1.8–9) km/hour. The scatter bands of the *95*% confidence level of the linear regression fits of the individual components represent 7.8, 5.1, 12.4% for $Y_1$, $Y_2$, and $Y_3$, respectively, and *41.5,* 7.5, and 7.6% for $X_1$, $X_2$, and $X_3$, respectively. The considerable scatter observed for the component $X_1$ is of no consequence to the criminalistic analysis of tracks, since the amplitude of this force is relatively very small and its corresponding shearing strain in the track will have been offset by the consequent deformation owing to the component $A_{x2}$, which has a considerably larger magnitude (up to 10 times).

- The relationships presented in the diagrams permit the maximum shearing forces, $A_x$, and forces of compression, $A_y$, acting on the surface in the three important phases of the foot/surface interaction to be determined for subjects of body weights between (400 and 1 050) N, walking with speeds within the experimental range. These maximum forces acting on yielding surfaces will result in specific patterns of deformation, certain aspects of which may be important for the analysis of tracks for criminalistic purposes.

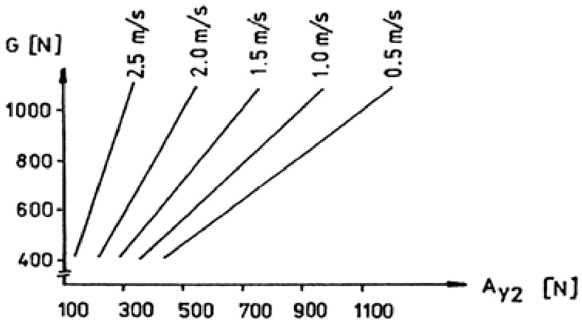

Fig. 2.31. The relationship between the vertical action force $A_{y2}$ acting in the medium phase of the foot/surface interaction and the force due to gravity, G, several speeds. Contrary to the other components of the action force, $A_{y2}$ decreases with increasing speed of walking (± 5.1% scatter at 5% significance level has been observed from the linear regression).

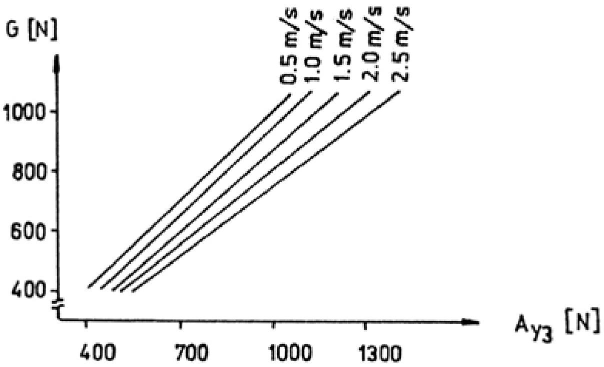

Fig. 2.32. The relationship between the vertical action force $A_{y3}$ acting in the final phase of the foot/surface interaction and the force due to gravity, G, for several speeds of walking (12.4% scatter from the linear regression at the 5% significance level).

However, no detailed description or visual presentation of specific features of tracks correlated directly with the above defined components of the forces involved in the interaction of bare or shod feet of a subject, of specific weight walking with a given speed, and a surface of known material properties can yet be presented.

Additional experiments would have to be performed, together with close monitoring of the specific features of the tracks, in order to achieve the goal outlined above:

- Presumably, when further data have been gathered, an empirical methodology of the analysis of the prominent features of tracks on deformable surfaces will become workable, according to which the magnitudes of the individual force components corresponding to the shape and extent of the observed features of the tracks could be assessed, thus indicating the body weight of the subject as well as his peculiar patterns of motorial behaviour. Additionally, all the necessary correlation's must be discovered between the size of the track, the height of the body, the force due to gravity, and possibly other somatic parameters, and also information derived from analysis of the sequence of the tracks must be utilized.
- No information on the distribution of the components $A_{xy}$ of the resulting action force is contained in the graphs currently available. This distribution of forces will have to be studied by other experimental techniques and methods of assessment for example, by combined application of a surface-pressure measuring device together with a suitable method of assessing local densities of the material in which the track has been formed or, possibly, by a newly developed device combining in itself the capacity to gauge both the surface pressures and the forces involved.

### 2.7.4 Methods of measuring the geometric features with biomechanical content for the analysis of tracks of bare feet

It was observed a long time ago in criminalistics that tracks of bare feet discovered at the scene of a crime under investigation cannot be unequivocally ascribed to a specific individual, since foot soles are elastic and are capable of conforming to the shape of the surface, to the type of locomotion and to the body mass. So far it has been assumed in the majority of cases that specific tracks can only be formed by feet misshapen by an inborn or acquired defect or by an injury Němec et. al. (1959).

Among the negative factors significant for the analysis of tracks of bare feet, the following effects involved in the interaction between the foot and the surface must be accounted for:

- the relative nature of the dimensions of the sole of the foot,
- the difference in values between planar and plastic tracks,
- the exact mechanism by which the track was formed.

The extent to which these individual factors affect the corresponding track differs in each particular case, depending mainly on the external conditions of locomotion, the shape and properties of the surface, the anatomic dispositions of the individual, the magnitude of the forces of interaction etc. The question of the relative nature of the dimensions of the soles of feet will be treated in more details below.

Methods of measuring the parameters of tracks of bare feet somatometric measurements aimed at enhancing the capabilities for individual identification of subjects according to tracks formed by bare feet have been undertaken within the scope of a research project directed at developing methods of appraisal of the biomechanical content of tracks of bipedal locomotion. The following parameters were measured (Czernych, Trofimchik 1976, Porada 1982) - foot size (represented by the length of the sole):

- the width of the sole,
- the arch of the foot,
- the angles of the heel and of the big toe,
- the angle of the sole.

The mechanism of formation of a track of a bare foot under stationary conditions can be considered as identical to that involved in obtaining a foot imprint under experimental conditions, during which the area of contact is distinctly outlined. Under stationary conditions, the foot rests supported by the balls of the toes, the heads of the tarsus bones, the outer edge of the sole, and the protuberance of the calx. A section of the area of the sole, including almost its entire inner edge, is arched. Fig. 2.33 shows one such imprint-called a plantogram together with an indication of the mechanism of its formation.

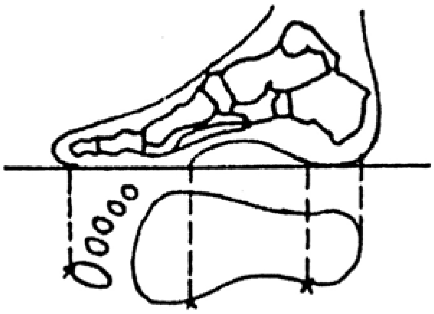

Fig. 2.33. The mechanism of for motion of a plantogram.

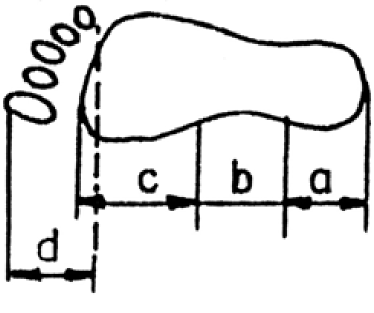

Fig. 2.34. The individual regions of the imprint; *a* the heel, *b* the isthmus. *c* the forefoot. *d* the region of the toes.

A more detailed distinction must be made between the individual regions of the plantogram, of which the following must be considered separately: the heel, the isthmus, the forefoot, and the region of the toes (Fig. 2.34).

A detailed description of a track is presented in Fig. 2.35, where the three points theoretically important in maintaining body stability are specified. The figure also provides a definition of the geometric parameters of the sole: the maximum width of the forefoot, the maximum width of the heel, and the maximum width of the isthmus.

The above defined parameters of the sole will be treated in detail. The size of the foot and its width *(l, w).* The measuring points of the foot defined above permit the length and width of the sole to be measured (see Figs. 2.36, 2.37). Owing to the considerable elasticity of the sole and the various specific processes involved in different mechanisms of track formation, these values are always relative.

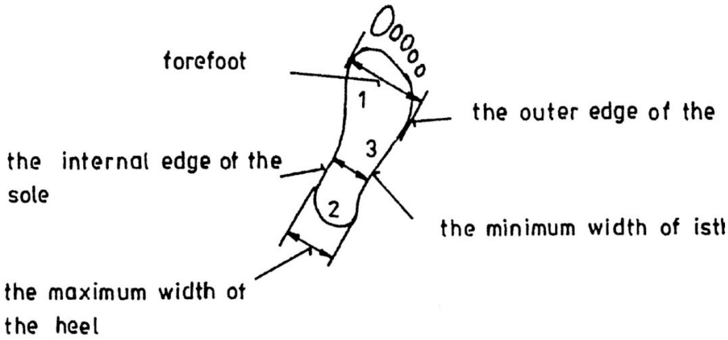

Fig. 2.35. Description of the characteristic areas of the imprint.

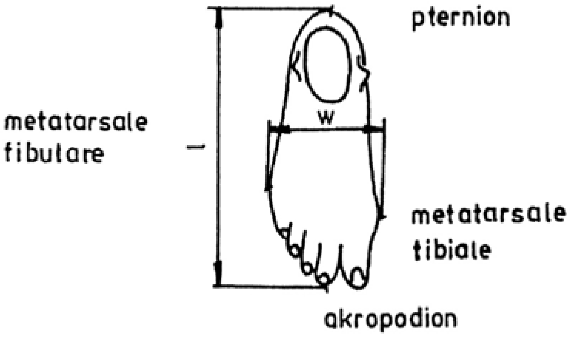

Fig. 2.36. The points of measurement on a bare foot for evaluation of the length and width of the sole (according to Fetter et al. 1969).

Czernych and Trofimczych (1976) presented an interesting guide for estimation of the overall sole length from fragments of tracks acquired at the scene of a crime. The correlations between the partial-length parameters and the overall length of the sole of the foot proposed by these authors are shown in Fig. 2.37.

*The arch of the foot.*

The most convenient method of assessing the arch of the foot has proved to be one that relies on comparison of established standards with experimental imprints. Fig. 2.38 demonstrates schematically one possible classification of the imprints of feet, according to Bunak (see Fetter et al. 1969).

The degree of flatness of the foot can also be assessed objectively by measuring the imprints. Shmirak (see Fetter et al. 1969) evaluated the ratio between the minimum and maximum widths of imprints. This ratio was reported to be in the range of 100 : 30 to 100 : 45 for a normal arch. A further method is provided by evaluation of the ratio between the area of the imprint an that of the entire sole etc. (Fetter et al. 1969).

Czernych and Trofimzcych (1976) assessed the degree of flatness of the foot by the method demostrated in Fig. 2.39. In this case, the value of the parameter of flatness is obtained by dividing the distance *XY* by *EZ.*

*The angles of the big toe and the heel.*

The angle of the big toe has been defined as the angle between the two straight lines a and b which are defined by the points *P. K,* and $K_1$ shown in Fig. 2.40.

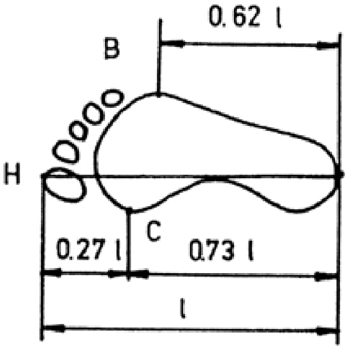

Fig. 2.37. Assessment of the length of a track of a bare foot from incomplete field data.

Fig. 2.38. A scale of imprints of bare feet.

The angle of the heel, $\beta$, has been defined as the angle contained between the straight lines a and *b* defined by the points indicated in Fig. 2.41. The points *D", D´* were defined in Fig. 2.39.

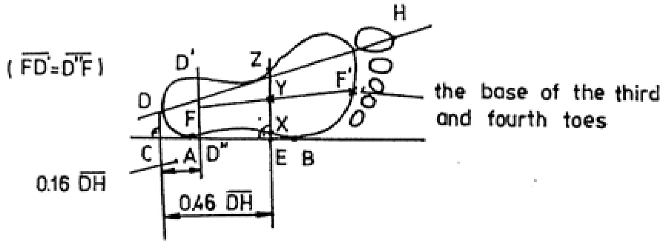

Fig. 2.39. Assessment of the degree of flatness of the foot from its imprint (according to Czernych and Trofimczych 1976).

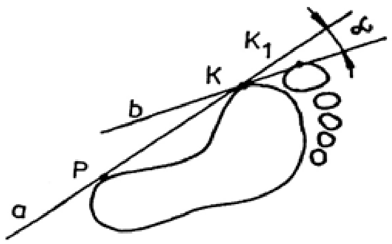

Fig. 2.40. Measurement of the angle of the big toe on an imprint.

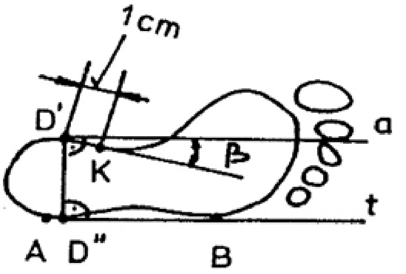

Fig. 2.41. Measurement of the angle of the heel on an imprint.

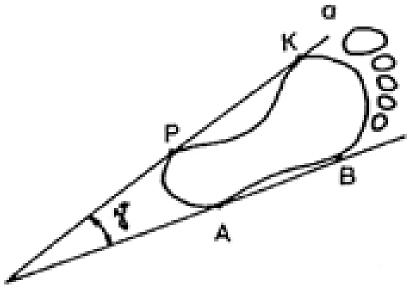

Fig. 2.42. Measurement of the angle of the sole.

*The angle of the sole*

The angle of the sole $\gamma$ has been defined as the angle contained between the straight lines a and *b* tangential to the inner and outer edges of the sole see Fig. 2.42.

*The relative nature of the dimensions of tracks of bare feet*

For the initial numerical analysis of the various dimensions of tracks of bare feet, some of the selected track parameters have been measured. These measurements were performed on a group of 30 adult subjects (males of ages between 30 and 40 years), each with a normal foot vault. The basic geometric parameters of plantograms of the right foot were obtained for various body positions:

P1-standing still, P2-maximum loading of the sole by the weight of the body, toes held tightly together, P3-the same as in the previous case but with toes held apart, P4-minimum loading of the sole, toes together, P5-minimum loading of the sole, toes apart, P6-standing on the outheredge of the sole, P7-standing on the inner edge of the sole.

Table 2.2. Measurements of a track of a bare foot.

| Measured quantities | Position | | | | | | | Sample mean | Sample st. Dev. |
|---|---|---|---|---|---|---|---|---|---|
| | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | | |
| Length of the sole of the foot (mm) | 242 | 246 | 248 | 283 | 234 | 226 | 235 | 238 | 7 |
| Width of the sole (mm) | 93 | 95 | 95 | 94 | 96 | 0 | 0 | 95 | 1 |
| Flatness | 0.71 | 0.75 | 0.68 | 0.88 | 0.85 | 0.97 | 0 | 0.81 | 0.1 |
| Angle of the big toe (°) | 15 | 12 | 9 | 11 | 9 | 0 | 19 | 12.5 | 3.8 |
| Angle of the heel (°) | 14 | 18 | 13 | 17 | 16 | 14 | 0 | 15.3 | 1.9 |
| Angle of the sole (°) | 18 | 17 | 18 | 18 | 17 | 0 | 0 | 17.6 | 0.5 |
| Width of the sole (mm) | 54 | 54 | 53 | 53 | 51 | 42 | 45 | 50 | 5 |
| Width of the isthmus (mm) | 24 | 19 | 18 | 19 | 21 | 17 | 0 | 19.6 | 2.5 |

The results of the experimental investigation for an arbitrarily chosen subject are presented in Table 2.2.

The data acquired from this set of experimental values demonstrate to a considerable degree the variability of the dimensions of imprints of bare feet on rigid surfaces for various body positions. On the other hand, the range of the possible variations of the measured parameters is certainly limited for each subject. The identification capabilities can be further improved by a precise description of the differences between the imprints of the right and left feet of the subject. The following pattern for the description of a track a bare foot, based on the experience gathered during the experiments, is proposed:

1. According to the character and width of the heel:
    a) according to its shape: egg-shaped, spherical, club-shaped, angular;
    b) according to the loading pressures: loaded in the forward or backward direction, from the inside, or from the outside;
    c) according to the width at the widest point;
    d) evaluation of the projection with regard to the longitudinal and transverse axes of the heel.
2. According to the character and width of the isthmus:
    a) according to the shape: circular, egg-shaped, pear-shaped, heart-shaped, quadrilateral, hexagonal;
    b) according to the continuity of the imprint: connected or disconnected;

    c) according to its width at the narrowest point.

3. Existence of the so-called third point and loading of the outer edge.
4. According to the character and width of the forefoot:
    a) according to the shape: oval, square-shaped, elliptical, irregular;
    b) according to the loading pressures: loaded in the forward or backward direction, from the outside, or from the inside;
    c) according to its width at the widest point;
    d) abnormal occurrences: traces of corns, or irregularities in pressures etc.
5. According to the character of the toe area:
    a) according to the shape: presence, partial or complete absence of imprints of the balls of the individual toes;
    b) accordings to the loading pressures: heavy, medium, or low;
    c) presence of irregularities: a toe missing or standing apart, etc. 6. According to the character of the muscle dynamics.

The relative nature of the dimensions of imprints of bare feet can be investigated also with regard of the shoes used and their size. The insole of the shoe continually reflects pressure changes. It follows that it can be regarded as a sort of summation imprint with characteristic features of its own. A shod foot represents a system of force transmission between the foot and the surface through an intermediary element, the shoe, by the impact of which the track is formed. The foot exercises pressure at the insole, the force is transmitted to the shoe, which than forms the imprint, or track, in the external surface. The superposition of tracks at the insole and at the external surface is shown schematically in Fig. 2.43, from which also the relative nature of the geometrical parameters is apparent.

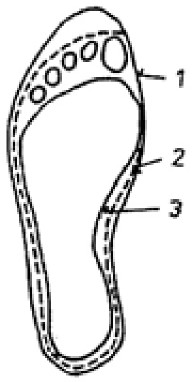

Fig. 2.43. An example of the superposition of tracks of the left foot of a subject.
1 - imprint of the shoe, 2 - the insole, 3 - the plantogram (Porada 1987).

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# 3 Forensic biomechanical application in criminalistics

## Introduction

The forensic application of biomechanics deals with the decoding of relevant criminalistic information originating in the vestige of penal action reflecting the functional and dynamic characteristic of the offender's or some other person's organism. The possibilities of application in accordance with the acquired experiences and literary research might be introduced followingly:

1. The assessment of the biomechanical content of the selected criminalistic vestiges; the up-to-now mostly analyzed is the biomechanical content of the trasological phenomena, partly even graphological print. Among these biomechanical applications might be classified even the mechanical behavior of the offender, his energetic output connected with the criminal act and his potential performance of movement viewing his abilities and limits of movement.

2. The extreme mechanical loading of organism, e.g. hitting by fist, stick or by some other object. Most frequently the attack is directed on the head of the victim. Analyzing these facts one must state whether the attacked person died instantly or survived and theoretically might have been rescued. It is important to determine and quantify the limit for possible survival after this cerebral mechanical loading of the victim's head structures.

3. The biomechanical estimation of falls from height most often out of the house window. It happens very frequently that the aggressor attack with the intention to kill and he throws the victim out of the window; during the investigation he defends himself by stating that the victim fell out by some unhappy chance. The biomechanical analysis may elucidate the fact of the involuntarily falling down or that there was an impulse and then that the victim was thrown out.

Current applications are primarily aimed at the development of both the theory of criminalistic methods and techniques for their practical implementation, as well as at the analysis of the traces of crime and the technical means of criminalistic identification, in the field of which special attentation has been devoted to methods of complex evaluation of traces.

The manner in which an individual criminal act is committed is of principal importance for its eventual discovery, investigation, and also prevention. During the investigation process itself, the motorial habits of the criminal represent a set of characteristics of paramount importance. It is self-evident that these habits are reflected the traces left by the criminal during his locomotion at the scene of the crime.

Since a criminal act is to perceived as one among many concurrent material processes of objective reality, it must be appraised as a section of a set of interdependent events, each reflecting the other phenomena of the set being considered and, on the other hand, affecting them to a certain extent. The material outcome of this mutual dependence is manifested through changes in the environment. Biomechanical deals with the changes caused by man.

The biomechanical content of traces becomes immediately obvious in the identification of a criminal by analysis of traces left by shod or bare feet, or of other similar imprints. Such tracks - originating during the interaction of forces between the foot and its pad, while the person is standing, walking, or running (static or dynamic tracs) - are amenable to analysis by biomechanical methods. Further studies in this area should certainly help to elucidate the existing mutual dependence between the geometric configuration of a set of tracks left by a criminal during his movements at the scene of a crime and some of his body characteristics, such as the physiological charakteristics of his legs and feet, body height, body mass etc.

## 3.1 Biomechanical contens of tracks of bipedal locomotion

During a close study of the tracks of human locomotion, both practical experience and logic lead us to assume that all material changes to the objects bearing the tracks reflect a certain portion of the somatic characteristic and pattern of the motorial behaviour of the individual whose action created the track. Such a record of some the biological attributes of an individual, together with his actual behaviour at the moment of the interaction that created the track, can be considered to represent the biomechanical content of the track. In this category belong primarily the geometrical, kinematical, and dynamical features of tracks.

The geometrical features will be found mostly in the spatial configuration of a track, or a set of track (a trail of locomotion), the most important characteristics being here those of length, width, and area of the track, or its depths (volume) in the case of plastic tracks, together with spatial correlations of a set of tracks, both in terms of distance and angular data. Also data describing the symmetry - or asymmetry - of the above mentioned parameters belong to this group.

The kinematical features will be manifested primarily in the frequence of the tracks, and from the correlation of these with other factors involved in the complex assessment of a track and of a set of tracks, the principal parameter of the velocity of the locomotion will be inferred.

Dynamic features involve the deformation of the pad caused by forces acting at the time the tracks, were mode with special emphasis on detailed study of the boundaries and central parts of the tracks, capable of indicating the various degrees of rolling or skidding involved in the motion, local compression of material etc.

## 3.2 The relationship between tracks of the feet and body height

Among recent works that have broadened the so far sparse basis for the analysis of the biomechanical content of tracks, enhancing the possibilites of criminalistic identification by these means, the most notable is that by Titlbach et al. (1978). The authors of this study have treated the question of the existence of relationship, and their numerical expression, between the dimensions of the soles of the feet and body height, between the dimensions of soles and shoes, and between the sizes of shoes and body height. The statistical analysis of this problem involved the following parameters: body height, mass of the body, length of the sole of the foot, width of the sole, shoe length, shoe width, shoe type, age. The individual geometric somatic parameters were measured either by common anthropometric methods or by means of a special device for the measurement of the dimensions of the soles of feet. These experimental data provided the basis for an evaluation of the statistical characteristics of the random variables involved, i.e. their mean values, standard deviations, and the average error in the mean. Furthermore, the length/width ratio of the sole, the difference between the length of sole, and the difference between the width of the sole and that of the shoe were computed. Statistical treatment of the final set data yielded information that seemed to indicate the following correlations:

1. Body height depends on both the length and the width of the sole.

2. With increasing body height the length of the sole also increases – withim a certain scatter – with the average rate of this increase being 2,5 cm/cm (increment of height against that of the length of the sole).

3. A simultaneous correlation exists between body height and the width of the sole, the ratio between the increments in body height and the width of the sole being 4,5 cm/cm.

The correlations defined above allowed an empirical to be constituted for the prediction of the probable body height of an average individual depending on data and the dimensions of the soles of his feet in the form of

$$h = 3,1\ l_S + 4,0\ w_S + 53,$$

where h represents the body height (cm), $l_S$ is the sole lengths (cm), and the width of the sole (cm).

The probabilistic relationship between body height and shoe size was determined in an analogous manner. This correlation can be expressed as

$$h = 2,6\ l_{sh} + 4,3\ w_{sh} + 55,$$

where $l_{sh}$ is the shoe size (cm) and $w_{sh}$ stands for the width of the shoe (cm).

These relationships allow the probable body height of an individual to be evaluated on the basis of numerical data on the dimensions of his feet or on the shoe size. The scatter band of these two correlation's lies within the ± 1 cm limits to the mean curve, which represents acceptable accuracy for practical purposes.

Probable height of a waking a person (normal stabilized steps, sport shoes with rubber sole; adapted after (h - height of the body; $l_S$ - lenght of one step; $l_{DS}$ - lenth of double step; $c_H$-$l_S$ and $c_H$-$l_{DS}$ - correlation coefficiens):

| Surface | Linear regression | $c_H$-$l_S$ | $c_H$-$l_{DS}$ |
|---|---|---|---|
| **Linoleum**<br>(house; velocity of walking 0,9-1,1 m/s; N=125 men aged 26-41) | **$h = 0,297\ l_S + 153$** ($l_S < 70$ cm) | 0,86 | |
| | **$h = 0,315\ l_S + 163$** ($l_S > 70$ cm) | | |
| | **$h = 0,157\ l_{DS} + 151$** ($l_{DS} < 142$ cm) | | 0,93 |
| | **$h = 0,175\ l_{DS} + 155$** ($l_{DS} > 142$ cm) | | |
| | **$h = 0,153\ l_S + 0,083\ l_{DS} + 155,5$** | | 0,89 |
| **Cinder** (athletic track; N=67 men aged 28-41) | **$h = 0,769\ l_S + 115$** | 0,76 | |
| | **$h = 0,437\ l_{DS} + 103$** | | 0,93 |
| | **$h = 0,384\ l_S + 0,218\ l_{DS} + 109$** | | |
| **Sand** (pit; N=67 men aged 28-41) | **$h = 0,497\ l_S + 136$** | 0,78 | |
| | **$h = 0,392\ l_{DS} + 112$** | | 0,81 |
| | **$h = 0,322\ l_S + 0,196\ l_{DS} + 118$** | | |
| **Snow** (soft; N=67 men aged 28-41) | **$h = 0,497\ l_S + 136$** | 0,62 | |
| | **$h = 0,368\ l_{DS} + 117$** | | 0,66 |
| | **$h = 0,248 l_S + 0,194\ l_{DS} + 126$** | | |

## 3.3 Assessment of the velocity of locomotion

The velocity of locomotion can so far be assessed only for the case of locomotion along a planar, horizontal, and stiff surface. There are several possibilities, available in the fundamental research, for an expression of the velocity of locomotion. All formulas listed subsequently require the values of the length of the step - or the jump in the case of running - to be known prior to assessment of the velocity of locomotion together with information on body height and the length of the leg (measured from the surface to the spina ilica anterior superior). The former of the two values can be evaluated by analysis of the sequence of tracks studied.

The general expression for the velocity of walking can be written in the form

$$v = f\,(h_{le},\ l),$$

where v - is the velocity of lomotion

$h_{le}$ - represents the length of the leg measured between the surface and the spina iliaca anterior superior,

l - is the lenght of the step.

The velocity of locotion expressed in terms of the two parameters defined above is usually gives by the linear relationship

$$v = k_1\ l + k_2\ h_{le} + k_3,$$

in which $k_1 (s^{-1})$, $k_2\ (s^{-1})$, and $k_3\ (m.s^{-1})$ are real constants.

**A) Evaluation of the velocity of locomotion**

With regard to application in criminalistic practice, the numerical values of these constants will be specified. From data published by Walt and Wyndham (1973) the following expressions for the velocity of locomotion can be derived:

For walking, either

$$v(km/h) = 11{,}63 \,.\, l - 11{,}30 \,.\, h_{le} + 8{,}32$$

or

$$v(m/s) = 3{,}23 \,.\, l - 3{,}14 \,.\, h_{le} + 2{,}31$$

is valid in the range from 0,88 to 2,2 m $s^{-1}$, while for running either

$$v(km/h) = 11{,}02 \,.\, l - 7{,}96 \,.\, h_{le} + 6{,}59$$

or

$$v(m/s) = 3{,}06 \,.\, l - 2{,}21 \,.\, h_{le} + 1{,}83$$

applies for velocities between 2,22 and 3,58 m $s^{-1}$.

Simpler realtionship, derived from sets of data by Cavagna and Margaria (1966) can also be used for a first approximation of the velocity of locomotion of and individual in the form of

$$v(m/s) = 3{,}89.\, l - 1{,}41$$

or

$$v(km/h) = 14{,}01 \,.\, l - 5{,}08$$

These two relationship are valid for the range of velocities between 0,83 m $s^{-1}$ and 2,7 m $s^{-1}$. All these correlations assume that the leg and step lengths are given in meters.

For the sake completeness, the derived formula published by Zaciorski and Selujanov (1978), using the time interval of the support phase of walking instead of leg length, will also be given, i.e.

$$v(m/s) = \frac{0{,}5l_0 - 0{,}528}{1{,}1.\, t_0.\, l + 0{,}31}$$

where $t_0$ - is the length in seconds of the time interval of the support phase,

l - again represents the length step in meters.

Neither of the above formulars at our current state of knowledge can be recommended as the one yielding the closets approximation to the true value of the velocity of locomotion, especially taking into account the existing differences between various populations. The final choice must be based only on experimental verification.

As follows from what has been said, the kinematical analysis of a sequence of tracks can be accomplished only after the leg length has been determined. One possible way is to assess this parameter from its correlation whit the body height observed for humans.

**B) Assessment of the length of the lower limb**

These above relationship derived from data published by Walt and Wyndham (1973) include explicitly the parameter of leg length $h_{le}$ (m). According to the data of these authors, there actually exists a correlation between the body height, $h_b$, and the length of the lower limb, which can be given as the linear relationship

$$h_{le} = 0{,}745\ h_b - 0{,}250,$$

for which the coefficient of correlation has the value 0,965.

Ross and Wilson have presented an extensive study aimed at defining the existing mutual correlations between the geometric parameters of the various parts of the human body. The basic concept underlying their work is one of thorough statistical evaluation of the proportions of the human body in terms of defined reference parameters. The statistical analysis of their anthropometric data has been used to define an ideal sexless individual, representing a union of parameters of the typical male and female figures. This proportionally "ideal" individual represents the reference model, bilaterally symetrical, the anthropometric data of which correspond to statistically average values for both lames and females, as measured by Garet and Kennedy (1968). The actual difference of an arbitrary segment from its reference value can be expressed by means of the so-called z-index, given by

$$z = \frac{1}{s}\left[ l\left(\frac{170{,}18}{h}\right)^{d} - p \right],$$

where z is the value of the z-index, is the actual value of the parameter describing the part of the body in question, s represents the standard deviation of the experimental set, h is the body height of the individual, d is an exponent the value of which is equal to for all linear parameters, 2 for all data on areas, and 3 for all parameters describing mass and volume; p is a reference value for the particular part studied.

The relationship for the z-index can be employed to assess the length of the lower limb, $h_{le}$, of an unidentified individual for whom the body height is known. Here z will be taken as zero, and hence from

$$0 = \frac{1}{s}\left[ l\left(\frac{170{,}18}{h}\right)^{d} - p \right],$$

follows the sought parameter

$$h_{le}(\mathrm{cm}) \ = \ \frac{p.h_b}{170{,}18}.$$

The specific numerical value of the parameter computed according to eqn. Must be regarded as stochastic in nature, and the corresponding standard deviation, s, must taken into consideration. For this model the value of the reference parameter, p, for the length of the lower limb is equal to 96,32 cm.

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# 4 Biomechanics of extreme dynamic loading on organism

## Introduction

The forensic application of biomechanics deals with the decoding of relevant criminalistic information originating in the vestige of penal action reflecting the functional and dynamic characteristic of the offender's or some other person's organism. The possibilities of application in accordance with the acquired experiences and literary research might be introduced followingly (Porada, Straus 2001):

1. The assessment of the biomechanical content of the selected criminalistic vestiges; the up-to-now mostly analyzed is the biomechanical content of the trasological phenomena, partly even graphological print. Among these biomechanical applications might be classified even the mechanical behavior of the offender, his energetic output connected with the criminal act and his potential performance of movement viewing his abilities and limits of movement.
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3. The biomechanical estimation of falls from height most often out of the house window. It happens very frequently that the aggressor attack with the intention to kill and he throws the victim out of the window; during the investigation he defends himself by stating that the victim fell out by some unhappy chance. The biomechanical analysis may elucidate the fact of the involuntarily falling down or that there was an impulse and then that the victim was thrown out.

In this contribution we would like to concentrate on the extreme mechanical load of the victim's head and on the tolerance of man's organism. Under the extreme dynamic situations is to be understood the toleration and resistance to the supercritical quantities of force, acceleration and pressure causing the injury of the organism, which might or could not be survived. Here we speak about lethal injuries. The limits of toleration being rather broad and individual the kinematic and dynamic analysis seems necessary together with the individual casuistic excess.

Among the very frequent injuries, we meet in criminological practice, are the head injuries caused by a blunt object. These blunt head injuries are significant partly for their exposed position and partly because nearly each time the attacked body part comprises a vital organ.

## 4.1 Balance of mechanical energy at external head impact

On analyzing the head injury it is necessary to respect the reality that the skull fracture need not be accompanied by a serious brain injury, on the contrary even mortal injury might exist without cranial fractures. Nearly all head injuries are accompanied by brain Injures.

At the arbitrary interaction force contact of a blunt object and man's head three phases may be distinguished from the mechanical point of view:

1) external dynamics – the motion of the object or head before the contact or hit,
2) proper hit – contact between the object and head, the transport of forces, energy of deformation,
3) the following phase – the motion of head or object after the hit (contact).

The attracting object is far stiffer or resistant than the attacked head of the victim. The attacking object moves with a certain kinetic energy, which is absorbed either by the soft tissue deformation or osseous cranial deformation, further the neck soft tissue may be deformed and finally a part of the kinetic energy cause the movement of the head.

The energy balance of the mechanical interaction may be expressed as follows:

$$E_P = \Delta E + E_{Po} + E_H \text{, where}$$

$E_P$ – kinetic energy of the moving object,

$\Delta E$ – energy consumed by the soft tissue of the head or by the deformation of the skull,

$E_{Po}$ – potential energy consumed by the tissue deformation of the neck,

$E_H$ – kinetic energy of head following the hit.

With regard to the fact that the hardness of the object exceeds the hardness of the man head tissued some part of the kinetic energy will be absorbed by the soft tissue deformation of the head or the skull fracture. The energy loss $\Delta E$ may be expressed (acc. to Jablonskij, 1977) as:

$$\Delta E = \left(1 - k^2\right) \frac{m_1 m_2}{2\left(m_1 + m_2\right)} \left(v_1 + v_2\right)^2 \text{, where}$$

$\Delta E$ – loss of energy by head tissued deformation,

$k$ – recovery coefficient,

$m_1$ – mass of the moving object,

$m_2$ – mass of the attacked head,

$v_1$ – velocity of the object closely after the hit,

$v_2$ – velocity of the head before the hit.

Provided the head will be motionless at the mechanical interaction, i.e. $v_2 = 0$, then the upper equation may be arranged as follows:

$$\Delta E = \left(1 - k^2\right) \frac{m_2}{\left(m_1 + m_2\right)} E_P \text{, where}$$

$E_P$ means the kinetic energy of the moving object. The absorbed deformation energy influencing the soft head tissues may be determined by the latter equation.

This energy depends on four factors:

- kinetic energy of the attacking object ($E_P$)
- mass of the attacking object ($m_1$)
- mass of the man's head ($m_2$)
- coefficient of recovery ($k$)

In assessing real casuistic the deformation energy may be calculated on basis of sufficient number of input variables. For the mass of head one may assess the relation according Zaciorskij-Selujanov (1978) by simplified expression:

$$m_2 = 1{,}296 + 0{,}0171\, m_T + 0{,}0143\, v_T \,,$$

where $m_2$ – is the mass of the head [kg],

$m_T$ – is the whole body mass [kg],

$v_T$ – height [cm] of the human being.

We may calculate the mass of the head more precisely as suggested by Karas-Otáhal (1991) following the linear regression function for the calculation of any arbitrary body segment ($i$ = 1, 2…) using the common formula

$$m_i = B_o + B_1 x_1 + B_2 x_2$$

All needed coefficients for the arbitrary height and body mass are introduced by the mentioned authors for the precise calculation of the head mass.

The recovery coefficient ($k$) characterizes the visco-elastic properties of the hitting object and human head. For the nonelastic hit (coefficient equals 0) consisting of one phase only, there exists no rebound of the object but only deformation. Such kind of mechanical interaction between the head and blunt object does not come on. Coincidentally, such mechanical situation between the perfect tough and elastic body when $k$ equals 1, does not come forth either. The hit is characterized by the coefficient ($k$) from an open internal (0,1).

The recovery coefficient ($k$) may be expressed by the velocity relation of the hitting object and head before the stroke and after it:

$$k = \frac{u_2 - u_1}{v_1 - v_2} \,,$$

where $u_2$ - is the head velocity after the strike,

$u_1$ – is the head velocity till the strike,

$v_1$ – is the object velocity till the strike,

$v_2$ – is the object velocity after the strike.

All the mentioned coefficients were experimentally verified by Korsakov (1991) on corpses using the recording by high-speed camera. His experimental results demonstrated that the velocity of the hitting object after the stroke was practically equal zero, the minimal back- or sidemovement was damped by holding, thus the formula could be simplified to

$$k = \frac{u}{v}$$

where $u$ – is the head velocity after the strike,

$v$ – means the object velocity after the strike.

## 4.2 Experimental data for different head injuries

Mogutov's experiments examined the strength of the strike and the subsequent characteristics of injury in corpses in 76 experiments distributed into three groups according to the spherical radius of the hitting device (3, 6 and 8 cm).

The analysis of the mentioned head injury enabled to formulate four basic groups characterized by the quantity and volume of injury. According to the analysis of the mechanical loading of cadaverous skulls we introduce a survey in tables that follow.

The first group is represented by the stab injury, the second by crater shaped wound geometrically copying the spherical object, the skull does not crack (break) only depression arises (Mogutov 1984):

Tab. 4.1.

| Diameter of the spherical object [cm] | Strength of strike [N] | Bone thickness [cm] |
|---|---|---|
| 3 | 9 986 | 0,68 |
| 6 | 6 605 | 0,63 |
| 8 | 12 691 | 0,68 |
| Medium value | 9 761 | 0,66 |

The second group of

| Diameter of the spherical object [cm] | Strength of strike [N] | Bone thickness [cm] |
|---|---|---|
| 3 | 7 457 | 0,53 |
| 6 | 7 183 | 0,51 |
| 8 | 8 389 | 0,57 |
| Medium value | 7 677 | 0,54 |

The third group creates a crater with radial infractions and the forth group with craters with transversal and radial infections

| Diameter of the spherical object [cm] | Strength of strike [N] | Bone thickness [cm] |
|---|---|---|
| 3 | 6 889 | 0,44 |
| 6 | 6 664 | 0,42 |
| 8 | 7 330 | 0,40 |
| Medium value | 6 961 | 0,42 |

The fourth group

| Diameter of the spherical object [cm] | Strength of strike [N] | Bone thickness [cm] |
|---|---|---|
| 3 | **7 428** | **0,45** |
| 6 | **7 311** | **0,44** |
| 8 | **6 978** | **0,37** |
| Medium value | **7 239** | **0,42** |

The second and third group of injury are characterized by the crater with dimensions, diameter and length may be precisely measured. These data are introduced in further table 4.1.

| Diameter of the spherical object [cm] | Second group of injury | | Third group of injury | |
|---|---|---|---|---|
| | **Max.** | **Min.** | **Max.** | **Min.** |
| | **[cm]** | | **[cm]** | |
| 3 | 2,2 | 1,8 | 2,5 | 2,3 |
| 6 | 2,6 | 2,5 | 3,4 | 3,0 |
| 8 | 3,0 | 2,8 | 3,8 | 3,4 |

We have only inadequate information on the motion velocity of the arm in striking action from sports and combat actions. We have always measured the whole time of the motion, of the completed motion action from its start till it has been finished when the hand has touched its target or reached its culminating motion. In order to conduct precise biomechanical assessment it is necessary to know the momentous impact velocity of the hand on the chosen target. Data on this final limit velocity of the arm and hand are yet unknown.

The value of momentous velocity of the strike by hand or by object (load) is necessary for prediction and calculation of the strength of the strike and consequent characteristics of the injury. That's why we have conducted our own measuring aimed at determining the momentous velocity of the hand in certain types of striking motion. The measuring has taken place in the criminalistic laboratories of the Police Academy of the Czech Republic on special equipment monitoring times of the motion of the arm at constant determined distances from the impact surface. We have chosen a fixed distance of 10 cm from the impact surface (Straus, Porada, 1999, Straus 2001).

We have conducted the experiment with group of 30 men a aged 21–45, of a standard somatic type the body height was chosen with the aim to divide the men into 3 groups according to the body height of 170 cm (10 persons), 180 cm (10 persons), 190 cm (10 persons), the variation being ± 2 cm. No participant has been extensively physically trained in any kind of sport.

We have divided the motion actions into two groups, labeling those striking actions where the strike had taken place without previous preparation index 1, with the frontal position of legs. Index 2 labels striking action where the stick took place from the lookout, the assailant being ready with the intention to strike. The starting time of the motion was subject to every participant's choice (Straus, Porada 1999, Straus 2001).

For the tables below we shall mark:

$t_1$ – duration of the motion action within the last 10 cm of trajectory before the impact, the strike being conducted without preparation;

$t_2$ – duration of the motion action within the last 10 cm of trajectory before the impact, the strike being conducted from the position of the combat alert, the assailant being ready with the intention to strike;

$v_1$ – final velocity of striking action for option 1 when the strike took place without preparation, frontal position of legs;

$v_1$ – final velocity of striking action for option 1 when the strike started from the position of combat alert, the assailant ready with an intention to strike.

Tab. 4.2. The hit strike coming from above, curved trajectory.

| body height | body weight | length of arm | t 1 | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,042 | 0,028 | 2,3809 | 3,5714 |
| 190 | 92 | 70 | 0,021 | 0,013 | 4,7619 | 7,6923 |
| 170 | 62 | 56 | 0,024 | 0,021 | 4,1666 | 4,7619 |

Tab. 4.3. The strike coming from above, curved trajectory, load 1 kg.

| body height | body weight | length of arm | t 1 | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,081 | 0,056 | 1,2345 | 1,7857 |
| 190 | 92 | 70 | 0,079 | 0,046 | 1,2658 | 2,1739 |
| 170 | 62 | 56 | 0,083 | 0,065 | 1,2048 | 1,5385 |

Tab. 4.4. The strike coming from above, upper arm levelled, fist above shoulder, no load.

| body height | body weight | length of arm | t 1 |  | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) |  | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,054 |  | 0,026 | 1,8518 | 3,8461 |
| 190 | 92 | 70 | 0,065 |  | 0,026 | 1,5385 | 3,8462 |
| 170 | 62 | 56 | 0,023 |  | 0,024 | 4,3478 | 4,1666 |

Tab. 4.5. The strike coming from above upper arm levelled, fist above shoulder, load 1 kg.

| body height | body weight | length of arm | t 1 | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,063 | 0,038 | 1,5873 | 2,6316 |
| 190 | 92 | 70 | 0,061 | 0,036 | 1,6393 | 2,7777 |
| 170 | 62 | 56 | 0,082 | 0,045 | 1,2195 | 2,2222 |

Tab. 4.6. Direct hit by a fist, no load.

| body height | body weight | length of arm | t 1 | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,031 | 0,022 | 3,2258 | 4,5454 |
| 190 | 92 | 70 | 0,034 | 0,031 | 2,9411 | 3,2258 |
| 170 | 62 | 56 | 0,038 | 0,031 | 2,6316 | 3,2258 |

Tab. 4.7. Direct hit by a fist, load 1 kg.

| body height | body weight | length of arm | t 1 | t 2 | v 1 | v 2 |
|---|---|---|---|---|---|---|
| (cm) | (kg) | (cm) | (s) | (s) | (m/s) | (m/s) |
| 180 | 78 | 68 | 0,067 | 0,054 | 1,4925 | 1,8518 |
| 190 | 92 | 70 | 0,085 | 0,059 | 1,1765 | 1,6949 |
| 170 | 62 | 56 | 0,12 | 0,089 | 0,8333 | 1,1236 |

## 4.3 Discussion of results and conclusion

The experimental data are necessary to the assessment of the biomechanical model of the tolerance of organism to the dynamical loading. The validity of this model depends on the variability of data acquired.

The most realistic variant of the mathematical model would certainly be appropriate to compare the results with empirical data. These possibilities are rather very limited as the corresponding data concerning the mechanical qualities of skull and brain substance are not available and the standards describing the brain injury are not known. Up to now the best expression of the critical values is under ”Wayne State Curve” described by Hiding–Wenner (1973). The mentioned curve describes the situation of a direct hit (stroke) of the head against a flat blunt object, and vice versa. The mentioned curve may be expressed as the time integral of an algebraic function, of the acceleration *a*(*t*), i.e.:

$$GSI = \int_0^t a^{2,5}(\tau)\, d\tau \,,$$

where the quantity *GSI* represents the skull loading stands for the acceleration.

The quantity *GSI* signalizes, from the empiric point of view, that any overcoming of its critical value ($GSI \geq 1000$) give rise to a very dangerous blunt impact. The load value of such head injury is represented by the function of acceleration. Some empirical data for short pulsatory intervals (2–5 ms) were obtained from experiments with corpses in which the skull fracture was taken as criterion of tolerance. For longer pulsatory intervals (approximately more than 40 ms) the data from volunteers tests were used in which case the light degree of brain commotions or unconsciousness served as criteria. The average pulsatory intervals were based on experiments with animals (dogs and apes).

The intracranial pressure following the strike changes along the ateroposterior axis at the impulse duration till 2 ms. At lower values ($t$ = 0,1 ms) has the pressure directly under the loading point a positive value, the interference does not reach the posterior part of the skull. At the strike by a blunt and solid object on the skull the pressure spreads in the interior and after certain time the pressure wave returns from the posterior wall and this pressure is denominated as negative pressure. This negative pressure reaches its highest values for $t$ = 0,8 ms. The highest negative pressure is on the posterior wall of the skull – of which fact follows, that the brain mass could be easily damaged by the tension or compression and the region on the contralateral part of the skull towards the loading point demonstrates higher degree of damage than the region of the stroke.

The type of the stroke in Wayne State Curve does not always correspond to the model and physical reaction (unconsciousness, commotion) is not precisely understood. No criteria exist to clarify the brain injury. The time interval of loading seems to approximate most precisely the criterion of brain injury. The negative pressure value in brain tissue depending on the intensity and duration of loading would sufficiently describe the process. Important data were obtained at loading tests carried out on fresh dead bodies after the autopsy in the range of frequencies 1–350 Hz (Hicling-Wenner, 1973). In order to calculate the influence of pressure in duration of some milliseconds it is necessary to know the loading function in the frequency interval from 0 to 2200 Hz. The time limit of load duration is 0,0022 s which load corresponds to the stroke action.

The experimentally reached results enlarge the contemporary basis of knowledge in biomechanics, criminalistics and forensic medicine.

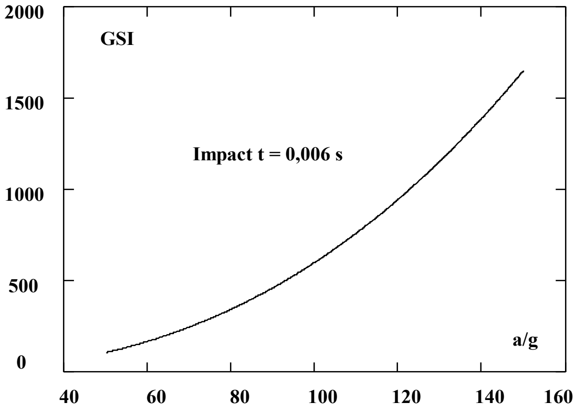

Fig. 4.1. GSI for impact t = 0,006 s.

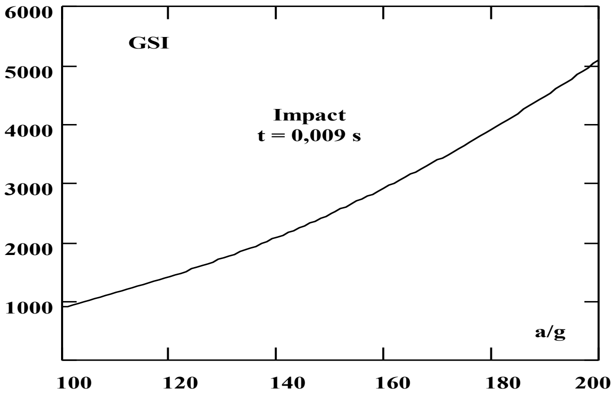

Fig. 4.1. GSI for impact t = 0,009 s.

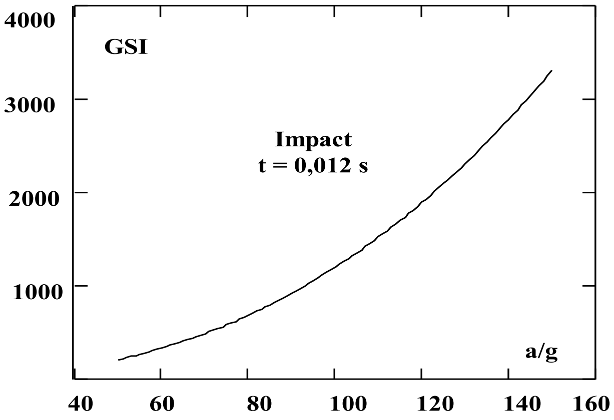

Fig. 4.2. GSI for t = 0,012 s.

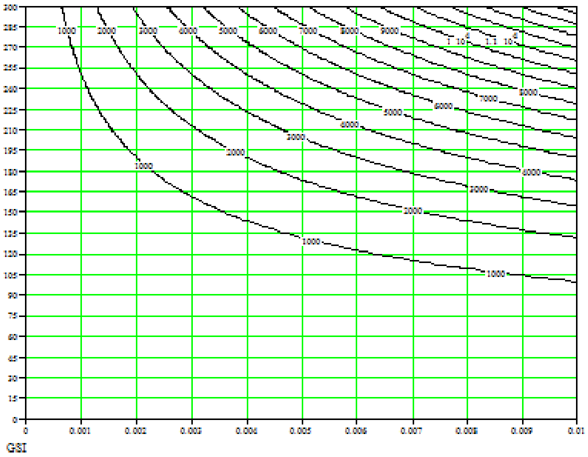

Fig. 4.3. GSI for $t_i$.

Tab. 4.8. Examples of different sort of critical values of tolerance, gathered from all sort of authors base on their mechanical and traumatic knowledge, shows the table.

| | Maximal value acceleration (m.s$^{-2}$) | Autor |
|---|---|---|
| comotio cerebri | a = 350 g | Schneider podle Ziffer (1955, 1957, 1964) |
| | a = 300-600 g (animals) | Chandler (1953) |
| | a = 280-400 g (monkey, cats)<br>a = 80-120 g ( mann) | Sellier-Unter-Harnscheidt (1962) |
| | Pressure intrakraniál (Pa) | |
| | 147 150 Pa for t = 6 - 12 ms | Lissner-Gurdjian (1966) |
| | 206 010 Pa for $t_{max}$ = 6 ms | Patrick (1966) |
| | Maximal value acceleration (m.s$^{-2}$) | |
| contusio cerebri | A = 350 - 500 g | Schneider podle Ziffer (1955, 1957, 1964) |
| | Pressure intrakraniál (Pa) | |
| | 196 200 Pa for t = 6-12 ms | Lissner-Gurdjian (1966) |
| | Maximal value acceleration (m.s$^{-2}$) | |
| infraction crania (with brain) at fall on concrete or steel board | a = 515 g | Ziffer (1956) |
| | a = 500 - 700 g | |
| | $F_{max}$ | |
| | F = 25 750 N | |
| | Maximal pressure | |
| | 858 375 Pa | |
| | Maximal pressure - temporal bone | |
| | 206 010 Pa | Haynes-Lissner (1962) |

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# 5 Biomechanical aspects of the falls from height

## Introduction

The fall of the human body from the height is based principally on the physical nature of the body's body litter. It is a composite motion, consisting of moving in a horizontal direction (in the x-axis direction) and a free fall. It carries the body to which we assign the initial velocity in the horizontal direction. Trajectories of motion are part of the parabola with the top in the throwing spot. The length of the litter depends on the initial velocity v0 and the height h from which the body was thrown. In the case of biomechanical evaluations of falls from a height, it is necessary to strictly rely on the laws of physics. For objective assessment of factors affecting the course of the fall of the body and the impact position, it is necessary to take into account the conditions under which the body contact was lost at the starting point. The fall of the body is determined at the moment when body contact with the pad is lost.

For forensic solutions to fall biomechanics, it is necessary to define the basic classification of falls and define some terminological problems of injuries and traumas arising from falls from a height. Depending on the height of the fall, the falls can essentially be divided into three groups, namely a drop from a stand, a fall from a height and a free fall. For Forensic Biomechanics, the most important are the drops from the height and the falls from standing.

An objective solution to the question of height and type of fall is possible in principle in two ways. On the one hand it is possible to create an optimal mathematical model and a theoretical simulation of the fall trajectory and body position at impact. Or maybe the second way, experimenting and simulating a fall with a suitable dummy that will meet the characteristics of the human body. This dummy can be dropped from a suitable Height and to assess the conditions of their own fall and the impact conditions. For the gain of serious scientific knowledge is then the optimal comparison of theoretical simulations with experimental data on the fall of the biomechanical dummy. A study was published in the literature that dealt with 30 cases of death due to a fall from a height. Information on the injury, including the height of the fall and the location of the body from the base of the building (horizontal distance) was obtained from police investigation files. Further inquiries were made of relatives and interceptors. The height of the fall and the distance of the body's impact were confirmed by measuring personally at the crime scene, for each case being studied personally (Kiran Kumar, Srivastava 2013).

Falls have been reported, for example, in one case, the father kept his baby in his arms on the balcony of his house when the child slipped out of his arms while trying to save the child from falling out of the balcony. In another case, a 10-year-old boy in a children's home slid on the railing along the staircase when he fell from a height of 5.1 meters. The thief climbed the eaves on the patio of the house and was revealed by the lady who slept on the terrace. When the shout started, the thief tried for a hurry to go down the same way back and fell from a height of 14.4 meters.

In most cases, the victim fell from a height of less than 10 meters (66.6%). A fall of more than 20 meters was registered in just 5 cases (16.5%). In most cases the victim fell near the building (76.6%) and 1 m from the base of the building.

Only in one case the body was found 8 meters from the building in which the thief jumped from the terrace (4th floor). To escape the police, he made a short-jump jump.

The majority of fatal deaths occurred in adult men aged 21–50 years. Most of the falls were accidental from balconies or terraces. The most common cause of death after impact on the ground was craniocerebral head injury.

Tab. 5.1. Relationship between fall height and horizontal distance of body impact (Kiran Kumar, Srivastava 2013).

| Fall Height (m) | Distance of impact from vertical drop (m) | | | | | |
|---|---|---|---|---|---|---|
| | 0 - 0,5 | 0,6 - 1 | 1,1 - 1,5 | 1,6 - 2 | > 2 | Total |
| 0 – 5 | 4 | 8 | - | - | - | 12 |
| 5,1 – 10 | 2 | 5 | - | 1 | - | 8 |
| 10,1 – 15 | - | 2 | 1 | 1 | 1 | 5 |
| 15,1 – 20 | - | - | - | - | - | - |
| 20,1 - 25 | - | - | - | - | 1 | 2 |
| 25,1 – 30 | - | 1 | 1 | - | - | 2 |
| 30,1 - 35 | - | - | - | 1 | - | 1 |

## 5.1 Biomechanical classification of falls

From the point of view of biomechanics, it is possible to classify the fall of a person into a variety of categories. Only two of them. Theory distinguishes mainly from a standing down, a fall from a height and a free fall. This division is logically based on the specifics of the different factors that act on individual cases in the course of the fall. Stalling occurs when the body is tipped over a tilting edge formed by a line that passes through a flat footrest. The body then falls to the front or back. In these cases the air resistance values are absolutely marginal and the height of fall of individual parts of the body is different. The height from which the head falls on the head is naturally the largest when the upright body falls, the height from which the lower body parts fall, then decreases proportionately. The most common task of Forensic Biomechanics in relation to standing falls is to determine whether the fall was spontaneous or whether it was caused by stroke. A fall from a height occurs when the body is on a raised floor with respect to the plane, and when the body flips around the tipping edge and releases it from the pad and then falls. Depending on the presence of the applied forces and their size, the body moves either through the parabola, the vertical, in exceptional cases the general curve. These are falls from relatively small heights, ie heights up to 150 meters. Throughout the fall, motion of the body is evenly accelerated, depending on the gravity constant, while the air resistance can be neglected.

As a fall, it is called the fall of a body from high heights over one hundred and fifty meters. The fall of the body corresponds to a certain point of the model of equally accelerated motion, so its speed is constantly increasing until it reaches its maximum. Experimentally, air resistance stabilizes the vertical velocity at falls from a height that is greater than 152

m. Then the air resistance equals the gravitational force FG = mg, and the speed of body movement is no longer increased.

In addition, it is possible to classify falls according to whether the body is inactive or active in fall or fall. In passive falls the body is at rest before leaving the support, and its fall is essentially determined by gravitational acceleration only. In case of active falls, the body is in the fall and at the moment of detachment from the pad in motion and besides the gravitational acceleration it is further accelerated by other forces. These forces are created either by the person's own active activity or by the action of other subjects, most often by the other person. The course of the fall depends mainly on the action and orientation of the force-acting vector and on how its acceleration is added.

The course of the fall is determined by the release of the body from the pad. From this point on, the body can take up either the vertical or horizontal position until the moment of impact, and it can also rotate during the fall. Rotation can occur in both passive and active falls. Its presence depends on various factors, but most often on the position of the center of gravity of the body when uncovering from the pad and on the size, direction and location of the force applied, especially if these forces act on or outside the center of gravity of the body. If there are other obstacle-forming bodies, such as parts of terrain, buildings, balconies, vehicles, etc., there is a so-called cascade collapse that causes the body to burst and change its path. The body is thus given secondary rotation. Impacted by fall, the fall may be slow. The body's impact on the ground mostly due to a strong impact on a certain part of the body occurs, depending on the height from which the body falls, to variously serious injuries. The first contact of the body after falling with the washer is called the primary impact. At the site of primary impact, the human body usually has a very high dynamic component of the force vector that is given by the impact velocity, body mass, and mechanical properties of the impact area. The subsequent impact of other parts of the body is referred to as secondary impact. With secondary impact, the lower impact force usually acts on the incident body part because the largest energy has already been absorbed at the primary impact site.

The vertical position of the body during the fall occurs most often to the impact on the legs (especially the heels), the knee, buttocks or the head. If the body falls horizontally, the impact on the front, back or side of the body is considered. The extent of the injury depends on the impact force, which is given by the body speed at the time of impact, the contact surface of the body and the washer, the mechanical properties and the shape of the impact area, the angle of incidence and the nature of the tissues affected by the impact. The force of a blow to the destruction of the organism is, in addition to the factors mentioned above, such as body mass and its impact rate, also dependent on the length of the time period during which the body speed is zero. It follows that the harder the impact area, the greater the destructive effect will occur.

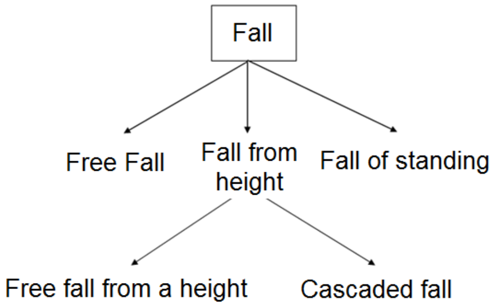
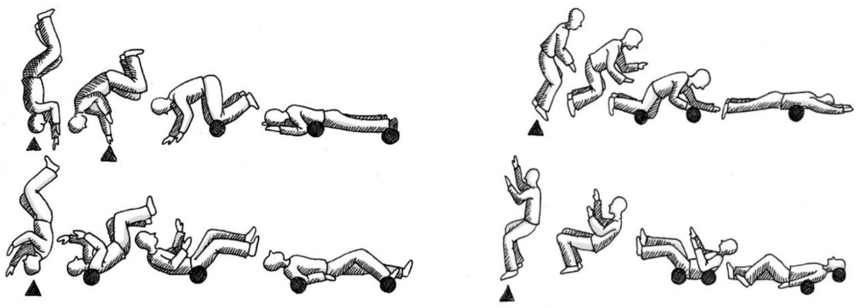


Fig. 5.1. Classification of falls (Straus 2012).

## 5.2 Injuries caused by falls

As a result of the collapse, regardless of the type of fall, two categories of injury are created: local, primary or remote, otherwise referred to as secondary. Local (primary) injuries arise at places of immediate destructive force at the moment of impact on the mat. Secondary or distant injuries arise at the sites of secondary impact of other parts of the body. On impact, the impact force is transmitted from the point of primary impact to the downstream part of the body even before the secondary impact of the other parts of the body occurs. This effect is noticeable, for example, in the vertical position where the body falls on the head or lower limbs. In both cases, the fall of the primary impact site, ie the head or the lower limbs, occurs in falls from height to devastating injury. However, due to the construction of the human support, the impact force is transferred to the spine, pelvic region and internal organs.



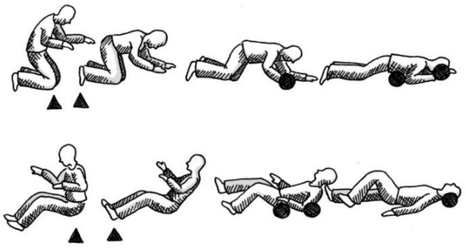


Fig. 5.2. The impact of the body and the representation of the primary (triangle) and secondary injury (wheel) (Straus 2012).

## 5.3 Fall from height

A fall from a height occurs when the body is on a raised floor with respect to the plane, and when the body flips around the tipping edge and releases it from the pad and then falls. Depending on the presence of the applied forces and their size, the body moves either through the parabola, the vertical, in exceptional cases the general curve. These are falls from relatively small heights, ie heights up to 150 m. Throughout the fall, motion of the body is evenly accelerated, depending on the gravity constant, while the air resistance can be neglected.

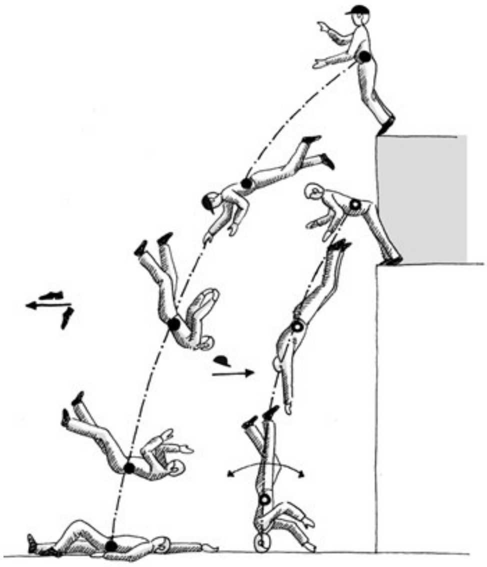


Fig. 5.3. Scheme of the fall of the human body from height (Straus 2012).

In the biomechanical assessment of the fall of the human body from a height, we consider quite often the fall of the body with the attached external force. The term applied force or force indicates the force that acts on the human body at the moment of detachment from the pad, and it can be developed by the person who falls, by his movement, or by another person acting on it. The vertical collapse or vertical is a designation for a convex line representing the perpendicular from the edge of the pad from which the body falls to the impact surface. If we are referring to a shift in the course of a fall, we mean the distance from which the center of gravity of the body moves from the starting position to the moment when the body leaves the support of the pad. Angle of tilt α when leaving the support is the angle which forms the vertical of a fall with a line that is the joint of the edge of the pad from which the body falls and of the total body center of gravity. The angle of impact β is the angle that is constrained by two lines when the body is at the water level. The first one passes through the point where the body first contacts the surface and is parallel to the perpendicular fall. The second line, is a link between the total body center of gravity and the intersection of the water level plane and the first straight line.

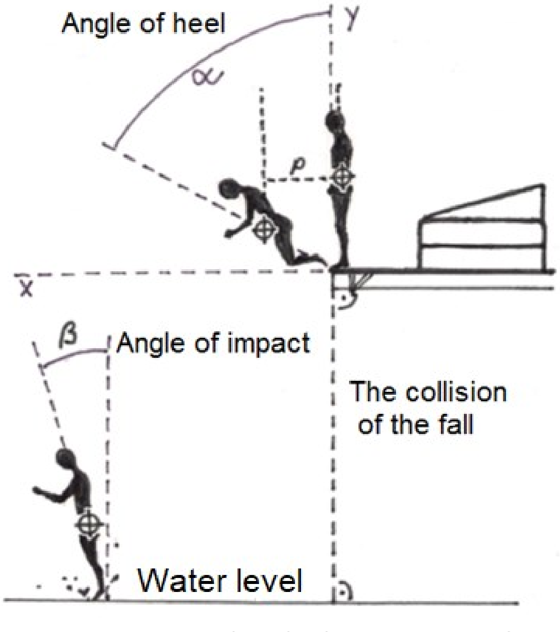


Fig. 5.4. Evaluating the course of the fall from the height (Straus 2012).

For all subsequent considerations, suppose that the body acts as an open kinematic chain when it falls. The center of gravity of the body moves along the parabola in the fall. From the position to the point of contact loss (usually the horizontal position), the body moves along the circle. Only the forces that arose at the moment of reflection act on the body. The fall of the body is from a relatively small height, and therefore the strength of air resistance can be neglected.

## 5.4 Physical basics of falling from a height

Horizontal litter - is a composite motion, consisting of moving horizontally (in the x-axis direction) and free fall. It performs the body to which we assign the initial velocity $\vec{v_o}$ horizontally.

Trajectories of motion are part of the parabola with the top in the throwing spot. If we plot this dish into the coordinate system with the vertex at x = 0; y = h, and point B, in which the body is located at time t, has coordinates:

$$x = v_0 t$$

$$y = h - \frac{1}{2} g t^2$$

The largest distance from the litter point is called the litter length d (point D, in which *x* = *d*, *y* = 0).

$$d = v_0 \sqrt{\frac{2h}{g}}$$

The trajectory depends on the initial velocity $v_0$ and the height h.

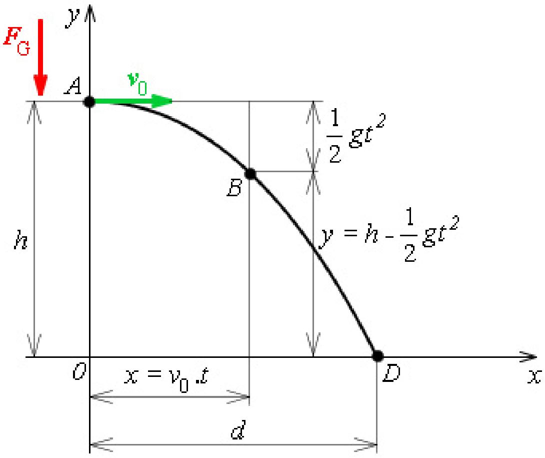


Fig. 5.5. Horizontal litter.

Angled litter upward - movement made up of movement obliquely upward and free fall.

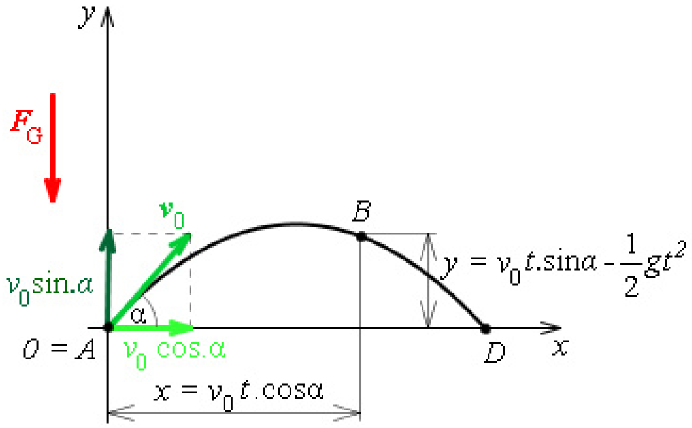


Fig. 5.6. Angled litter upward.

The initial velocity $\vec{v_o}$ has a direction which makes an angle α; with the horizontal direction; this angle is called elevation angle. The trajectory of motion is a parabola (only in a vacuum) whose peak is the highest point of the trajectory. In the air, the body describes a so-called ballistic curve (due to air resistance).

After plotting the parabola into the coordinate system, we find that for any trajectory point:

$$x = v_0 t \cos\alpha$$

$$y = v_0 t \sin\alpha - \frac{1}{2} g t^2$$

Litter length:

*x* = *d*, *y* = *0*, then : $v_o t \sin\alpha - \frac{1}{2} g t^2 = 0.$

From this equation we calculate the time of impact: $t_d = \frac{2v_o}{g}\sin\alpha.$

Once we have reached the litter, we get the litter length: $d = x_d = v_o t_d \cos\alpha = \frac{2v_o^2}{g}\sin\alpha\cos\alpha$ = $\frac{v_o^2}{g}\sin 2\alpha.$

We determine the time of exit from the condition that it is at this point $v_y = 0$.

Then : $v_y = v_o \sin\alpha - g t_v = 0$, $t_v = \frac{v_o \sin\alpha}{g}.$

$$y = v_o t_v - \frac{1}{2} g t_v^2$$

$$h = \frac{v_o^2 \sin^2\alpha}{2g}.$$

However, the human body has different mechanical properties than a rigid physical body. The general characteristics and physical laws will apply to the fall of the human body, but it is necessary to slightly correct them according to the biological characteristics of the human body. That is why it is necessary to schematize the situation, to simplify and to carry out model experiments with a biomechanical dummy whose weight ratios of the individual body segments will be the same as the living body. If we analyze in greater detail the whole situation of a person's fall from a height, then in a natural, uncoordinated fall, the body first pivots about an axis forward and falls only when the contact of the feet with the fall site is interrupted. The body (and therefore the center of gravity of the body) describes ideally a quarter circle, and when the body's longitudinal axis is in the horizontal position, the center of gravity trajectory turns into a dish.

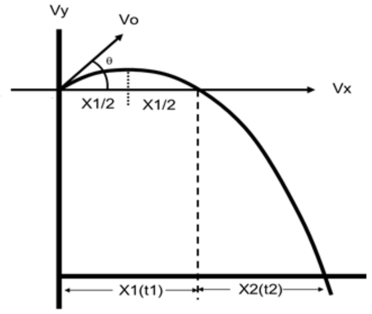


Fig. 5.7. Fall Schedule (Modified by Kiran Kumer, Srivastava, 2013).

The initial speed can be calculated from the height and the horizontal movement in the event of a fall at various angles with the speculative formula:

$$vo = (gx2/2(x.\sin\theta - y \cos\theta) \cos\theta)\ 1/2$$

The solution to the question of biomechanics of falling from a height is very important and crucial for expert investigation in forensic biomechanics. If the response is to be serious, objective and appropriate to real conditions, it is necessary to have sufficient input information available for the subsequent biomechanical solution to the fall issue. This issue has not yet been satisfactorily solved, the current results correspond to the experiments in which a height drop with a training dummy was modeled, whose mass parameters, dimensions and location of the center of gravity were the same as the living person.

For the experiments, a training dummy was used, used by wrestlers to practice technical-tactical shuffle actions in the game. The biomechanical dummy was constructed in such a way that the individual body segments corresponded to the live weight ratio of the man and the position of the manikin's overall center of gravity corresponded to the location of the center of gravity of the living person.

The generalized results correspond to a sufficient number of experiments - free uncoordinated falls from two different, fixed heights, 7–8 meters and 10–11 meters, which corresponds to a fall from the second or third floor of a standard building. In the experiments, the aim was to determine and specify the free uncoordinated fall trajectory depending on the height of the fall, the starting position of the body at the onset of the fall, the site of the primary impact, the center of gravity of the body from the vertical to the point of origin of the fall, the position of the body at the secondary impact, the force, the place of the vector's field of external force.

For the experiments and the fall modeling scenes, three starting positions were selected for the beginning of the fall:

1. Fall of the window sill, the dummy was tilted from the vertical axis to 10° forward, followed by a free uncoordinated fall from the heights of 7.3–8.1 meters or 10.4–11 meters.
2. A balcony balcony from 10.4 to 11 meters high, with 10 kg (98.1 N) external force (stroke) attached. The external force vector was attached to the shoulders, the center of gravity, or the knees. This simulated a situation where a man is struck by a force of 10 kg in his shoulders, center of gravity or in his knees.
3. Fall from the "dream-on-hand" position from the balcony rail from a height of 10.4–11 meters.

In the first case, forward velocity $v_1$ = 1.37 m / s, in the latter case forward velocity $v_2$ = 1.78 m / s. For these values, it is possible to express a linear relationship for calculating the probable forward velocity of the body's center of gravity during free uncoordinated fall.

One form of a possible fall from a height is that at the moment of contact loss the outer body is attached to the body. This situation will occur in those cases where a person fights back. For free fall, there are physical laws that can be described by equations for motion evenly accelerated by gravitational acceleration (g). Considering that external forces are exerted on a person at a moment, then we will consider for the subsequent consideration that they must be reflected either from the spot or with the start, and thus the body is given an external force that causes the initial velocity of the $v_0$.

When jumping with the attached external force, the jumper is reflected upwards, the body's center of gravity trajectory (and the whole body) first flies up the parabolic curve upwards, and when it reaches the peak, it falls down. The maximum horizontal length of the jump can be affected by the size of the initial velocity vector and the angle $\alpha$. The length of impact is deterministically determined by three factors, namely the height of the jump, the magnitude of the reflection velocity and the magnitude of the reflection angle.

In principle, there may be two types of jumps, namely a long jump with a start and jump into the distance from the place (the so-called swimming jump). Initial jump distance with a start of 9,15 ± 0,11 and a jump of 2,70 ± 0,11 m / s, the angle of reflection was found to be 21° ± 0,40° and to jump from 38° ± 1.33° (Shaw, Hsu 1998).

Jumps from high heights are either suicidal jumps or unfortunate accidents when people want to overcome some distance. The reflection point, the reflection angle, the point of impact, and the height are the main determinants that can be used to determine the type of fall.

## 5.5 Analysis and experimental results

Biomechanical studies were conducted by thirteen athletes through biomechanical measurement to test the running jump and standing jump (swimmer’s start jump) (Shaw, Hsu [31]). The initial velocity of the running jump and standing jump in normal athletes is 9,15 ± 0,11 and 2,70 ± 0,11 m/s with jumping angles of 21 ± 0,40 and 38 ± 1,33 deg, respectively. The practical measurements of horizontal velocity of the running jump and swimmer’s start jumpo were 8,54 ± 0,07 and 2,10 ± 0,05 m/s and vertical velocity, 3,88 ± 0,12 and 1,59 ± 0,07 m/s, respectively. These results suggest an initial velocity between0 m/s for the standing jump and 9,15 m/s for the run-up and jump that may contribute to launch the fall from a height by a voluntary (suicidal) jump. The initial velocity of 9,15 m/s can be defined as the maximal value of a normal individual engaging in a fall with a pre running acceleration before launch.

Tab. 5.2. Biomechanical studies of standing (swimmer´s) jump and running (long) jump (Shaw, Hsu 1998).

| Biomechanical Maesurement | Swimmer´s Jump (n = 9) | Long Jump (n = 30) |
|---|---|---|
| Initial angle (deg) | **38,00 ± 1,33** | **21,00 ± 0,40** |
| Initial velocity (m/s) | **2,70 ± 0,11** | **9,15 ± 0,11** |
| Horizontal velocity (m/s) | **2,10 ± 0,05** | **8,54 ± 0,07** |
| Vertical velocity (m/s) | **1,59 ± 0,07** | **3,88 ± 0,12** |

**Standing Jump** - To present the typical standing jump, without adding any running activity, selective modes of the swimmer’s start jump provide unique jumping patterns that emulate the jumping activities through which the biomechanical measurements are obtained. Although many scholars have demonstrated how to find the initial velocity in sports that include a standing jump, the standing swimmer’s jump represents a distinctive pattern of jump from a height that can truly emulate the jump of falling from a height. A standard standing broad jump can generate up to 3,60 m/s of initial velocity at an angle of 41,03 deg on the basis of the body gravity of normal athletic students. The swimmer’s start jump, an ideal model to mimic the standing jump and falling from a height, makes it almost impossible to adjust the body position while the jumper has already left the jumping point, and thus permits us to measure the initial velocity and order related biomechanical parameters, including both horizontal and vertical velocity as well as jumping angle. Distinct body gravities may explain the lower value of the initial velocity of the standing jump while we compare the initial velocity of the standing broad jump with an adjustable gravity. A two-hand push of a normal individual to other individuals (70 kg of body weight) can generate an initial velocity up to only 0,4 m/s (Chen 1987). An initial velocity exceeding 2,70 m/s or so becomes the criterion for the running jump that is distinguishable from being pushed or sliping before falling from a height. For distance, an initial velocity lower than 2,70 m/s cannot be distinguish between suicide, homicide or accident (Shaw, Hsu 1998).

**Running Jump** - The running jump is a situation where is a running start to a jump from a height when an individual is really out of his mind or has convinced himself to jump from a height. This jump is preceded by a pre-running acceleration before launching to result in an intentional fall. When an individual actually launches at maximal force, the maximal horizontal movement can reach 42% of the height (42,21 m away from the jumping point while falling from a 100 m height at an angle of 11,44 deg with an initial velocity of 9,15 m/s). A running jump initial velocity that reaches 9,15 m/s reasonably explains the maximum capability of normal athletes. An initial velocity between 2,70 and 9,15 m/s support a jumping activity with pre-running assistance before the jump. Such data permit us to determine the pattern of fall and jump. Any initial velocity exceeding 9,15 m/s should be carefully evaluated for other reasonable explanations, including wind factor, an inaccurate jumping point, a fauly impact point, launching machine assistance, etc. It is evident that falling after a running jump is a manner of intentional jump. Therefore, the decendent´s attempt to commit suicide should be considered. A falling fatality with an initial velocity exceeding 2,70 m/s should not be mistaken for accidental or homicidal cause of death (Shaw, Hsu 1998).

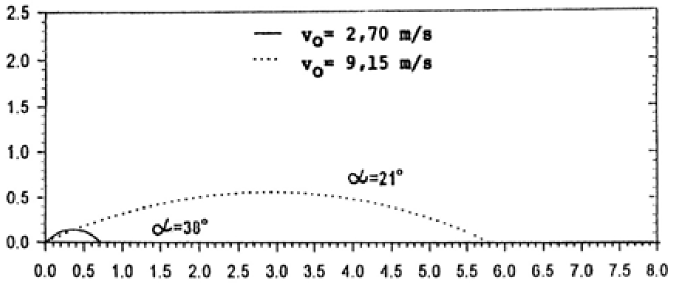


Fig. 5.8. Falling patterns of standing jump and running jump above the jumping level: Running and standing jump are intimated at initial velocities of 9,15 and 2,70 m/s at initial angles of 21 at 38 deg above the jumping level (Shaw, Hsu 1998).

Initial velocities from 2,70 to 9,15 m/s may explain the running activity before jumping as well as the conviction of intentional running and jumping. Besides, it does become the standard criterion to charakterize the voluntary jump as well as the suicidal fall. The initial velocities estimated from these experiments of standing and running jumps allow us to distinguish the jumping patterns of deaths caused by high falls. The difference between the standing and running jump can be recognized as the mental status of the jumper, including the determination or hesitation of the jumper’s thoughts. The results of biomechanical studies suggest that in initial velocity over 2,70 m/s is a critical point for a voluntary jump while 9,15 m/s is a cutoff point of maximal physical capability for an intentional jump. An initial velocity over 2,70 m/s in a voluntary jump, with the help of pre-running acceleration before the jump, suggests that the attempt to commit suicide is considerable. The initial velocity can be derived from the height and horizontal distance of falling at various speculative angles by using eq. In conclusion, in every case, both the horizontal distance of movement and height should be used to estimate the initial velocity, to reconstruct The difference between the standing and running jump can be recognized as the mental status of the jumper, including the determination or hesitation of the jumper’s thoughts. The results of biomechanical studies suggest that in initial velocity over 2,70 m/s the falling pattern, and to theorize on the manner of death so as to rule out the suicidal jump (Shaw, Hsu 1998).

Tab. 5.3. Maximal horizontal movement and initial jumping angle varies with height at constatnt initial velocity of standing and running jump (Shaw, Hsu 1998).

| Height (m) | Standing Jump **$v_0$ = 2,70 m/s** | | Running Jump **$v_0$ = 9,15 m/s** | |
|---|---|---|---|---|
| | $\alpha_{max}$ (deg ) | Horizontal Movement(m) | $\alpha_{max}$ (deg) | Horizontal Movement (m) |
| 0,0 | **45** | **0,74** | **45** | **8,54** |
| 0,05 | **33,15** | **1,14** | **43,42** | **9,03** |
| 1,0 | **27,50** | **1,43** | **41,99** | **9,49** |
| 3,0 | **18,37** | **2,24** | **37,47** | **11,15** |
| 5,0 | **14,74** | **2,83** | **34,17** | **12,59** |
| 7,0 | **12,66** | **3,31** | **31,62** | **13,88** |
| 10,0 | **10,72** | **3,93** | **28,68** | **15,62** |
| 20,0 | **7,7** | **5,51** | **22,76** | **20,36** |
| 30,0 | **6,31** | **6,72** | **19,45** | **24,20** |
| 40,0 | **5,48** | **7,75** | **17,26** | **27,50** |
| 50,0 | **4,91** | **8,66** | **15,67** | **30,45** |
| 60,0 | **4,49** | **9,48** | **14,46** | **33,14** |
| 70,0 | **4,16** | **10,23** | **13,49** | **35,62** |
| 80,0 | **3,89** | **10,94** | **12,69** | **37,95** |
| 90,0 | **3,67** | **11,60** | **12,02** | **40,13** |
| 100,0 | **3,48** | **12,22** | **11,44** | **42,21** |

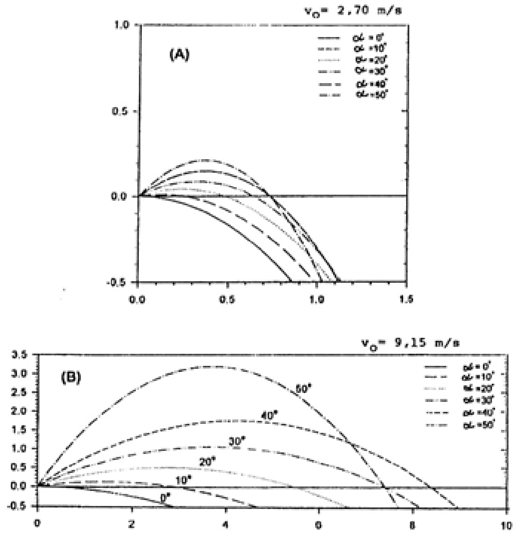


Fig. 5.9. Falling patterns intimated at various angles of jump at initial velocities of 2,70 m/s (A) and 9,15 m/s (B): Maximal horizontal movement can be achieved at about 40 deg; the angle at 50 deg or over starts to minimize the horizontal movement (Shaw, Hsu 1998).

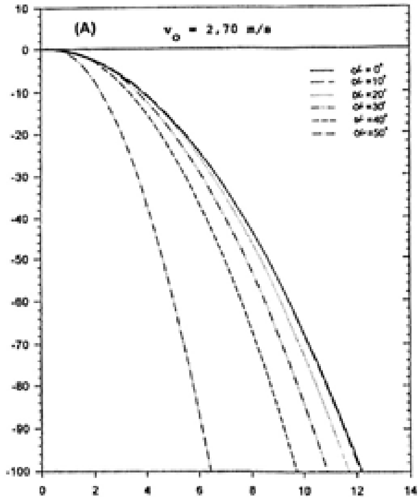


Fig. 5.10. (A) - Falling patterns intimated at various angles of jump at initial velocities of 2,70 m/s (A) and 9,15 m/s (B), falling from height of 100 m (Shaw, Hsu 1998).

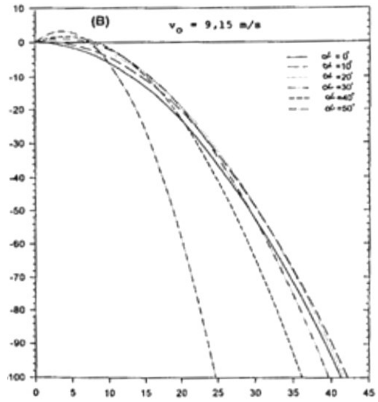


Fig. 5.11. (B) - Falling patterns intimated at various angles of jump at initial velocities of 2,70 m/s (A) and 9,15 m/s (B), falling from height of 100 m (Shaw, Hsu 1998).

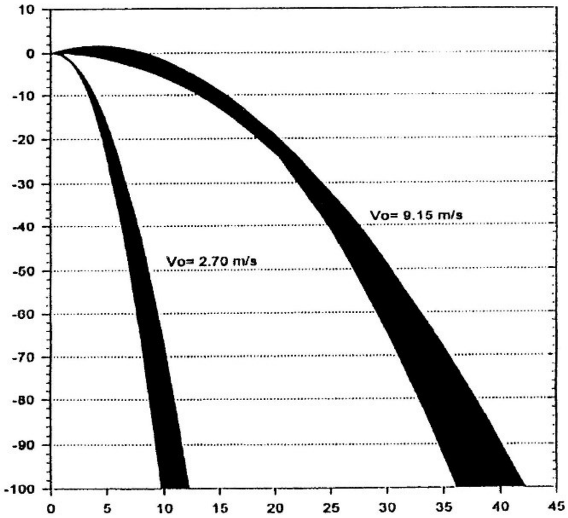


Fig. 5.12. Range of maximal horizontal movement of standing jump and running jump at angles between 0 and 40 deg (Shaw, Hsu 1998).

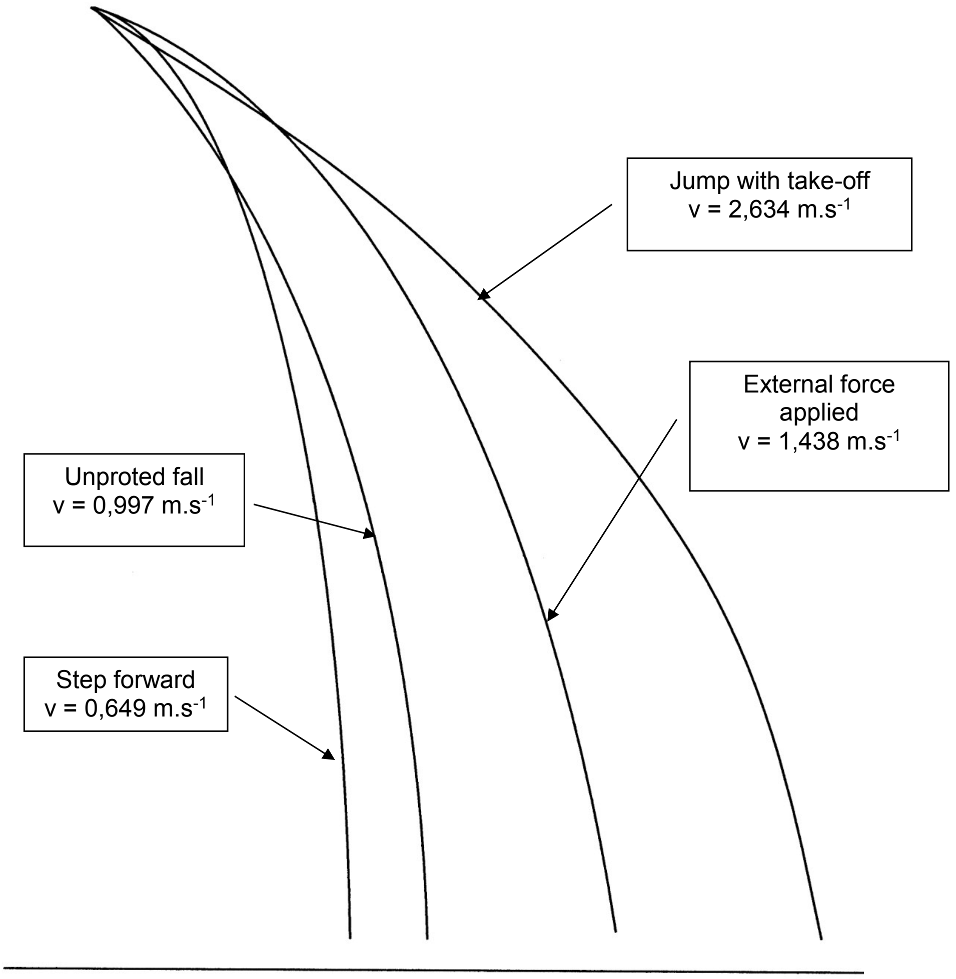
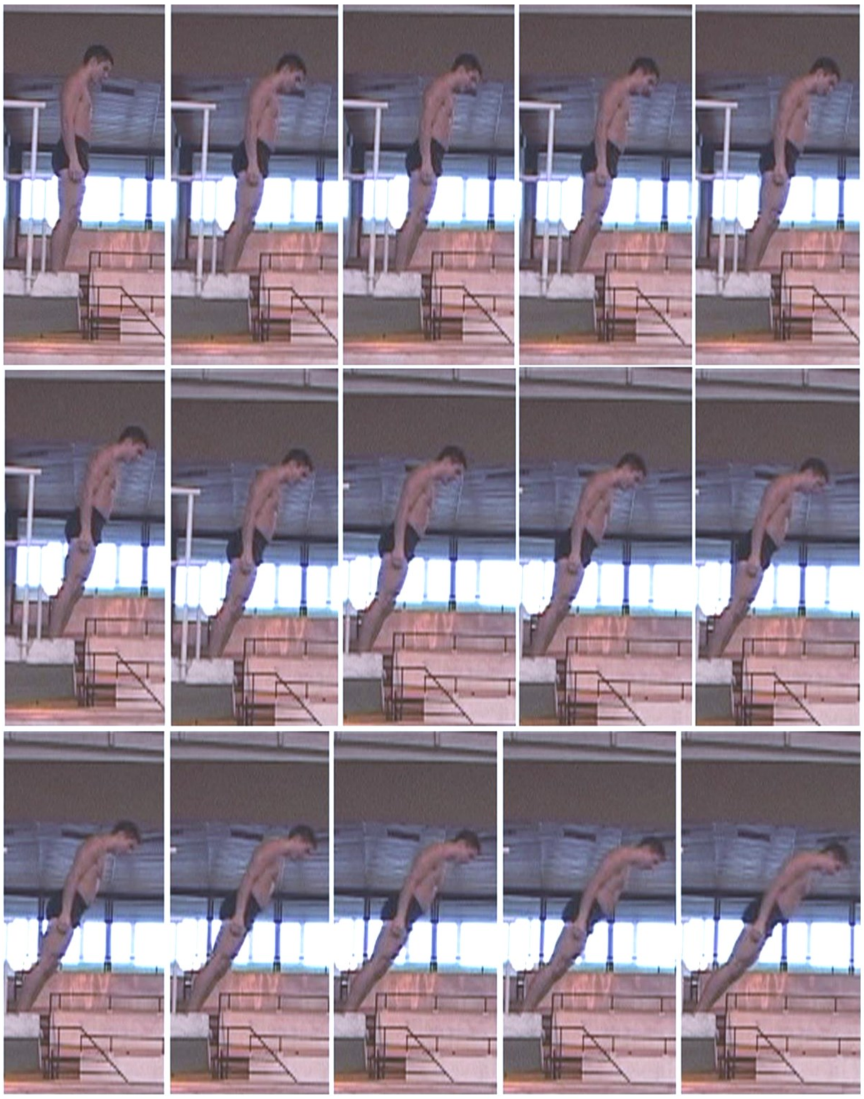


Fig. 5.13. Body mass center trajectory comparison as relation of different kind of falls.



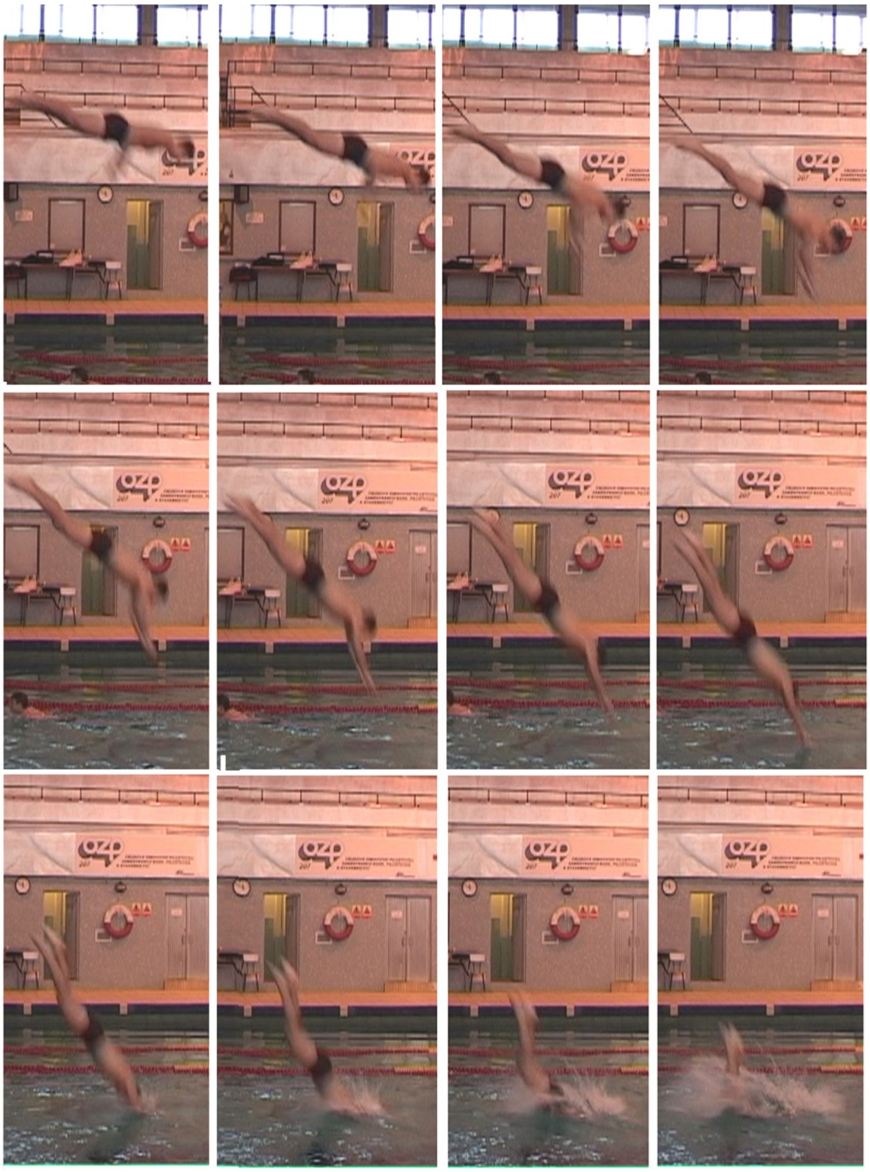


Fig. 5.14. Unproted fall, $v = 0{,}997\ m.s^{-1}$, $t_i = 40$ ms.

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# 6 Standing on a pad

## Introduction

In the analysis of falls and head injuries in extreme dynamic loads of humans, a separate direction of investigation is formed by a group of falls that occur when the body is tipped around the tilting edge formed by the line passing through the flat surface of the feet. If there is no flexion in the knee joint (the person does not flex the knee) and there is no flexion in the hip joint, then the center of gravity of the body moves along a part of the circle. In the fall from a vertical standing position to a horizontal position, the body's longitudinal axis is tilted 90 ° and the center of gravity of the body moves along the quarter circle. In these cases, the body falls on the surface of the abdomen or the back, and the biomechanical analysis is the dominant blow to the head and the associated consequences.

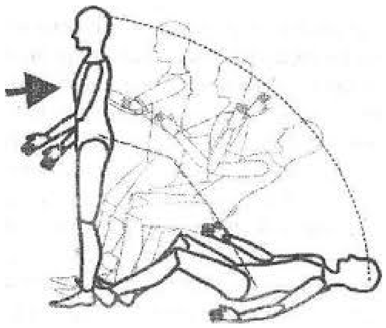

Fig. 6.1. Scheme of dropping the body from stand to pad (Zarubin 2003).

From the point of view of practice needs, the most common way is a fall from a standing position that causes a head injury, a fall back. The man falls from behind, falls on his back, and the greatest force strikes his head. In this type of fall, the person does not hold the head in the safe position with the neck muscles and, in the event of impact, strikes the head as a result of very strong dynamic forces. In the course of a movement, the falling person does not coordinate in the vast majority of cases, falls spontaneously, chaotic, and moves bow in his back, curls his head, in this case falls backwards on his head. The highest dynamic load then receives only the occipital portion of the head of the falling person. Exceptions may occur in the case of a very small group of specially trained athletes, especially junior sports (judo, wrestling, karate), who are specially trained on this type of fall and react reflexively, the fall damping by coordinated movements. They are perfectly capable of stunning, shock-absorbing, collapsing body when falling, and head-to-head contact does not come into contact with the right fall back technique. In the other considerations, we will not consider this type of fall, from a biomechanical analysis point of view we will be interested in the crisis variant of the fall, in which the person strikes the head.

The essence of the biomechanical assessment is the assessment of the possible fall, head impact on the ground and the occurrence of the injury. The angular velocity of the falling body is:

$$\omega = \frac{4,92}{\sqrt{L}}$$

o calculate the peripheral velocity of movement of the center of gravity of the head segment (vr), it is necessary to base the general relationship:

$$v_r = \omega \ . \ r_o$$

If we know the distance between the center of gravity of the head and the rotation axis, it is possible to express the peripheral velocity of the head center of gravity movement during a spontaneous fall. According to biomechanical data (Korsakov 1991, Sažajeva 2008): the distance considered can be expressed as

$$r_o = 0,94 \ L$$

Then you can enroll:

$$v_r = \omega \ . \ 0,94 \ L = \frac{4,92}{\sqrt{L}} \ . \ 0,94 \ . \ L$$

After editing, we get it (Korsakov 1991):

$vr = 4,62 \sqrt{L}$ or very precisely $vr = 4,417.L^{0,49}$

## 6.1 Mathematical modeling of a fall from a stand on a mat

Mathematical modeling of the whole process and simulations of the human body by the mechanical model can express the magnitude of the forces that act at the moment of falling into the person's head. Calculation of the impact force is best suited to the theoretical modeling proces from the empirically derived inputs, and compare the resulting computation with those literary data that were obtained, for example, by stroke. The experiments confirmed the expected and logical conclusion that the destruction time of the head varied depending on the surface hardness, it was found (Gromov 1979):

a) For the hard surface it is $t_i$ = 0,006 - 0,007 s.

b) For the semi-hard surface $t_i$ = 0,007 - 0,009 s.

c) For a soft surface $t_i$ = 0,021 - 0,030 s.

From the known time of head destruction in the fall, it is possible to calculate the probable magnitude of the force that acts on the head of a person when falling back from the stand on a pad of varying quality of elasticity. The calculation of the force size depends on the weight of the person (G), resp. weight and body height (*L*) (Gromov 1979).

a) For the hard surface it is $F = (7{,}7 \pm 0{,}6)\ .\ G\ .\ \sqrt{L}$

b) For the semi-hard surface $F = (5{,}6 \pm 0{,}7\ )\ .\ G\ .\ \sqrt{L}$

c) For a soft surface $F = (1{,}6 \pm 0{,}3)\ .\ G\ .\ \sqrt{L}$

Experimentally, these values, procedures, and formulas were verified by dropping the biomechanical dummy into a strain gauge plate that sensed the magnitude of the force generated by head stroke at the fall. Differences between the calculation and the measured values were minimal, ie 50 kg, and the formula can therefore be accepted for forensic biomechanical analyzes.

From the point of view of forensic biomechanical assessment of the fall from the stand on the pad, it is necessary to consider the case when the person is accelerated by the applied vector of force located above the center of gravity of the body. In practice, this is the case where a person is struck in the head, for example by blowing his fists, kicking his foot, blowing open his palm or some object. As a result of the strike, the head curves, the body bends downwards, and the impact on the pad faces the main blow to the head part of the head. The most common site of destruction of the skull is in the area of the lamb seam.

## 6.2 Bend and fall from stand

Falls caused by disruption of attitude or walking are a relatively frequent phenomenon in forensic biomechanics. In the Czech criminal area, 15% of cases are dealt with in forensic biomechanics. This issue is not used only in criminal cases, but also in civil cases, for example in the fall caused by alleged slipping on the surface, in which a knee or hip injury occurs, when it is necessary to determine the mechanism of the fall, which often took place without further witnesses. The case was also described when slipping into the head, and consequently the cause of the fall, which was underpinned by incomplete testimony, was extremely small, especially in comparison with established biomechanical models. Therefore, it is necessary to know the typical and appropriate features of individual disruptions.

The following figures show kinematic values of motion - the movement of the head and the body's body during fall.

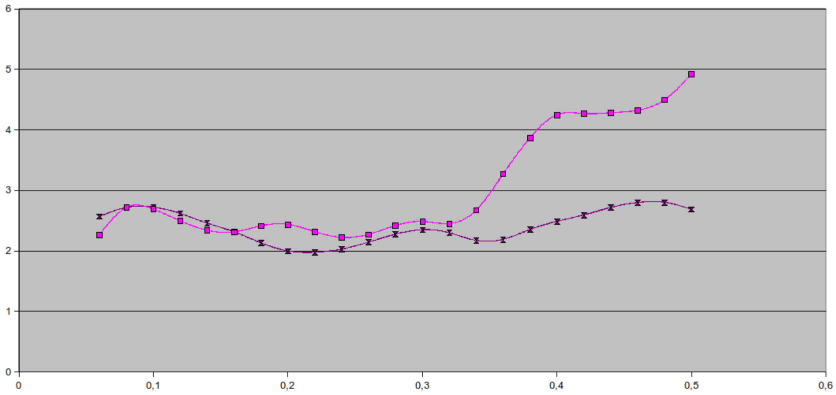

Fig. 6.4. Typical course of head velocity and center of gravity over time, y axis: speed (m / s), axis x: time (s).

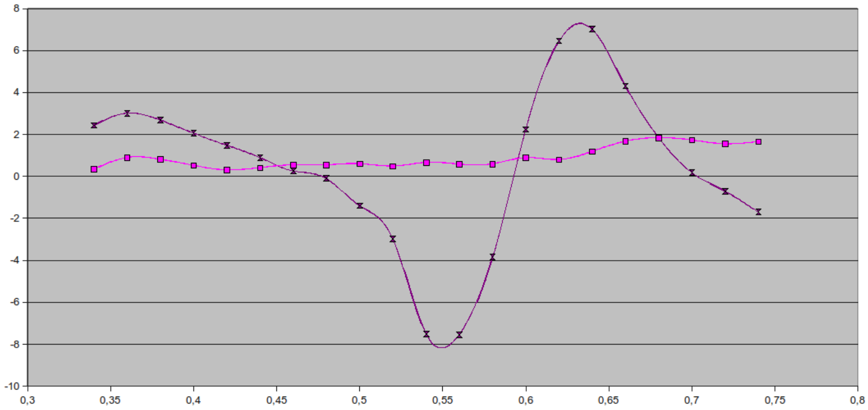

Fig. 6.5. Typical course of the angular velocity of the head and the angular velocity of the resting limb over time, in case of restored stability (walking speed: 6.9 km/h, response time: 0.08 s), y axis: angular velocity (rad / s), axis x: time (s).

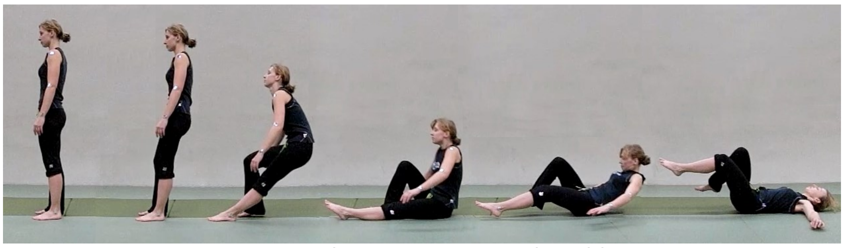

Fig. 6.6. The course of the spontaneous fall of figurant No. 3.

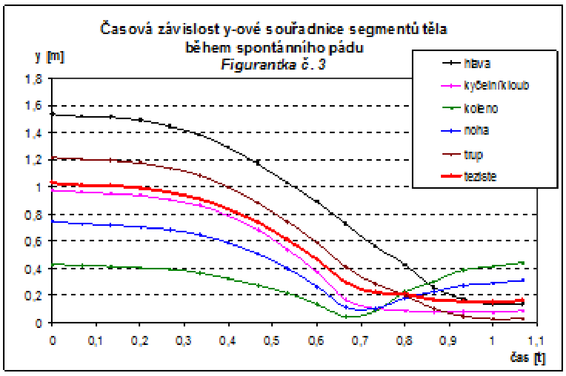

Fig. 6.7. Time Dependence y-Coordinates of Center Body Weight During Spontaneous Fall.

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# 7 Human reaction time

## Introduction

Free reactions to the stimulus are much more complex than reflexes and require higher brain function. In case of free reactions, the signal from the eye or other sensory organ, resp. several sensory organs at the same time, is sent to the motoric centers of the brain that process it, determines the nature of the response, and transmits the given instruction to the muscles, which then perform the reaction, after a certain period of time. However, the response to a given stimulus does not react with a muscle reaction immediately but with some delay. The length of the reaction time is physiologically limited and, to a certain extent, influences the speed of the entire movement (in fact, the total duration of the movement), which is extremely important especially for short-duration movement movements of the order of seconds. Response rate is also extremely important in solving motor activity involving large muscle groups (Straus 2001).

In forensic biomechanics, in recent years, the issue of addressing external and internal responses to reaction time has emerged as a very topical issue. As the current factor we consider the influence of alcohol on the decision time, ie the reaction time is a complex motor response.

## 7.1 Concept of reaction time

The simplest is the reaction time (Danko 2013) the time that elapses from the beginning of the perception of the stimulus to the beginning of the response to the stimulus. The expanded concept of reaction capability was provided by Human Factors Design Handbook defining a simple reaction time as the shortest possible time between the moment the senses detect the stimulus and the time at which the body begins to respond, while the complex reaction time additionally involves the process of human thinking. It is further characterized by the fact that the role of the complex reaction time is to create several stimuli with different modes of response.

The distribution of simple reaction times and selective reaction times with a simple motor response is revealed by the fact that the visual information process is the most important part of the human reaction capacity. Additionally, the optional response time includes a decision making process that logically causes delay, thus comparing with a simple reaction time, the overall reaction rate increases. Moreover, the time needed for the decision is the most variable component of the reaction rate. However, this difference provides an approximation of the determination of the decision time interval, according to specific conditions, respectively. the number and type of factors that will be further elaborated in this work. The most important factor here is the kind of incentive, because the need to make decisions based on a more or less standard incentive makes this component unstable compared to other components (Demirarslan 2008).

The total reaction time can be expressed as the sum of the duration of the visual perception and the duration of decision-making that the motor response itself is immediately following. Visual perception includes the interval needed for the detection of the stimulus since it was detectable, while the decision time represents the time needed for selection and response decisions. Then the body starts the performance of the corresponding response. Above the definition of reaction time, the time required for muscle movement is built up, which nevertheless constitutes an unavoidable category, since exploring only the reaction speed without interest motor responses would be lost to forensic biomechanics of practical significance.

Expressing reaction velocities in the terms of these components is as follows:

$$t_{rt} = t_p + t_r ,$$

$t_{rt}$… reaction time

$t_p$… the time required for perception

$t_r$… time needed for decision making

## 7.2 Categorization of reaction times

Donders in his publication (Donders 1969) first proposed a classification scheme from which experts continue to describe and distinguish between response rates:

- simple - consisting of the stimulus itself, to which the subject responds as quickly as possible, immediately after the discovery of the stimulus;
- recognition - consisting of two or more stimuli, but with only one response corresponding to one stimulus, while the rest can not respond;
- selective - consisting of two or more stimuli to which the subject must make different responses, ie the subject must choose what signal was present and then make the response appropriate to that stimulus.

The scheme concerned and continues to concern experimental psychology and closely related science disciplines. In a simplified way, this branch can be included in reaction times, the essence of which is a motor-friendly, and a terminologically slightly different scheme can be expressed in Fig. 7.1.

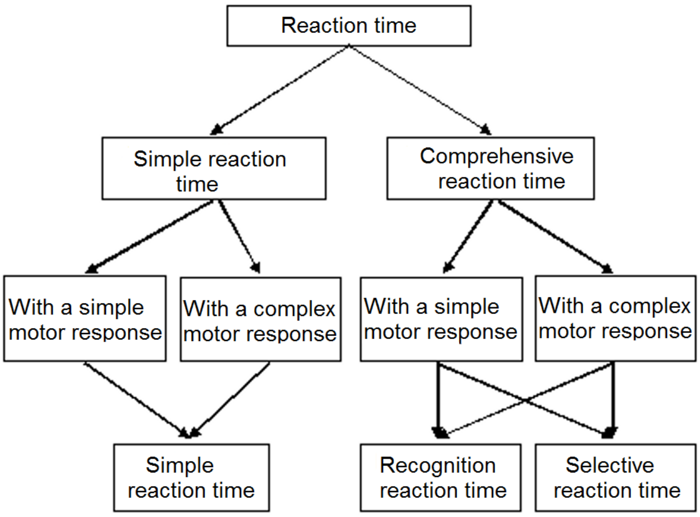
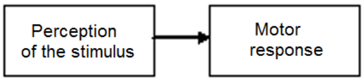


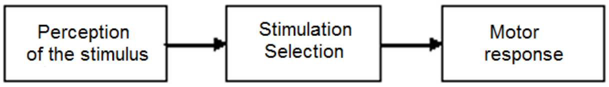
Fig. 7.1. Categorization of reaction times.

Response rate with complex motor response characterizes a situation where the subject engages in response to a large muscle group, unlike simple motor responses where it is absent.

Simple reaction time



Recognition reaction time



Selective reaction time

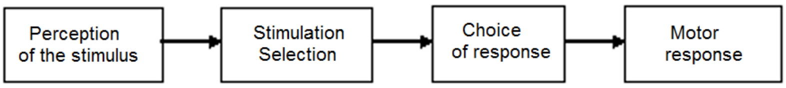


Fig. 7.2. The process of motor response formation for each type of reaction time, according to Donders (1969).

## 7.3 Components important to the duration of the action

From the point of view of a relevant event, whether traffic accidents or conflict fighting analysis, it can create next to these components another important category of latency caused by the device. If a person performs a response by means of an instrument, then they form an inseparable system together with the human being, and the duration of a human reaction can not be considered to be relevant. Most often, given these examples, it is certainly a means of transport or a firearm.

The basis for the interpretation of the components includes, without question, the elucidation of the essence of perception, since perception is the basic process of man and the reaction by the initiation process in response to any stimulus. The most important types of perception are visual and auditory perceptions.

## 7.4 Visual perception

Visual perception is the most important in many situations. The entity obtains basic information about the situation. However, the eye has different areas of distinction. In this context, we talk about central and peripheral vision. The central, frontal vision has a range of only a few degrees at the highest level of sharpness. For optimal use of this vision, the subject needs to constantly change the direction of vision. Peripheral, detection, general vision, on the other hand, captures the entire area outside the conical central vision. Visual perception is the most important for identifying information important for further decision making, which, as mentioned, plays a significant role.

The general process of vision is as follows (Porada 2000):

- the eye is oriented in the field of view with volatile micro-movements;
- the external stimulus attracts attention;
- the visual receptor focuses and focuses on an interesting optical stimulus and, on the basis of the detected optical parameters of the optical situation (distance, brightness, etc.), is prepared for reception;
- the stimulus processed by the optical system of the eye will hit the luminescent elements of the retina;
- the transformation of the optic stimuli in the nerve impulses generates a response in the optic nerve, which leads to the brain centers of vision where the sensation is generated;
- synthesis generates a perception, on the basis of which the organism's response to the given stimulus is decided, so-called differentiation occurs;
- the sensation can be lost or stored in memory or can be transformed into anxiety, spreading with the movement nerves to the neuromuscular plaques;
- in neuromuscular plaques, nerve impulses are transformed into nervous contractions;
- during the process the central nervous system is constantly informed

- about changes in the properties of the observed object and its surroundings; sends commands, controls the adaptive state smoothly.

Theoretically, a role can also be played by perceptions within so-called "foveal vision," where the whole yellow spot does not come to the picture, but only in its part called the central well and only suppositories are filled. In this section, the highest quality display of items is displayed.

## 7.5 Hearing perception

Hearing perception allows the subject to retrieve information that would be difficult to detect by the sight, either because it did not work, so he would not be able to handle it. Audio information, unlike optical, is perceived unconsciously, inadvertently, without the intention of registering it.

The hearing organ consists of three parts: the outer, the middle and the inner ear. The outer ear consists of the bolt and the ear canal and ends with a drum. The outer ear captures the sound of the drum. This part of the auditory organ, along with the shadow of the head, influences the intensity of the stimuli coming to the drum from different directions, so it is important for the directional characteristic of the auditory organ. The sound is best received from the party and somewhat from the front. Directional effect occurs at high frequencies, while tones deep, up to 200 Hz, perceive on all sides at the same volume. The middle ear has a transfer and protective function. The string of three auditory bones transmits and amplifies the vibration of the drum into the oval window of the inner ear. The sound energy is collected from a relatively large area of the drum, it concentrates on a small area of the oval window, and virtually no losses passes into the middle ear fluid. If a strong sound comes to the hearing organ, the two muscles will withdraw in a reflective fashion. This increases the tension of the drum and makes it difficult to transfer, especially deep tones. It happens at sound levels of 65 - 85 dB. Throughout the moment of stimulation, the perceptiveness of strong sounds is reduced, and the labyrinth is protected from damage. Reflex has a latency of 10-150 ms. However, for the sounds of impulse nature (duration up to 200 ms), this protective function of the middle ear is not actuated, so it is easier to damage the inner ear.

The minimum sound level audible to the human ear is called the audible threshold, which corresponds to a sound pressure level of 10-5 Pa. If the intensity of acoustic waves on the ear increases, the perceived noise becomes louder and louder, when the hearing around the 120 dB stops and changes into ticking, so that the tactile sensation also occurs in the hearing organ, which is referred to as the tactile threshold. However, if the hearing sounds for long periods of time, the threshold of audibility is already in the first minutes. Adaptation is taking place and the noise is perceived at a lower volume. This adaptation phenomenon is followed by another storyline - hearing fatigue that occurs already in the first minute and reaches its saturation in a period of 7 to 10 minutes. It also involves altered differentiation of frequencies, volume and change of camouflage. It recedes in tens of minutes, hours and sometimes lasts all day.

## 7.6 Duration of action and its components

The total duration of the action can be sequentially subdivided into separate sections for didactic purposes. These sections are the reaction time, the duration of the motor response and facultative latency caused by the device. Clearly, this complex is represented by the following scheme (Figure 7.3):

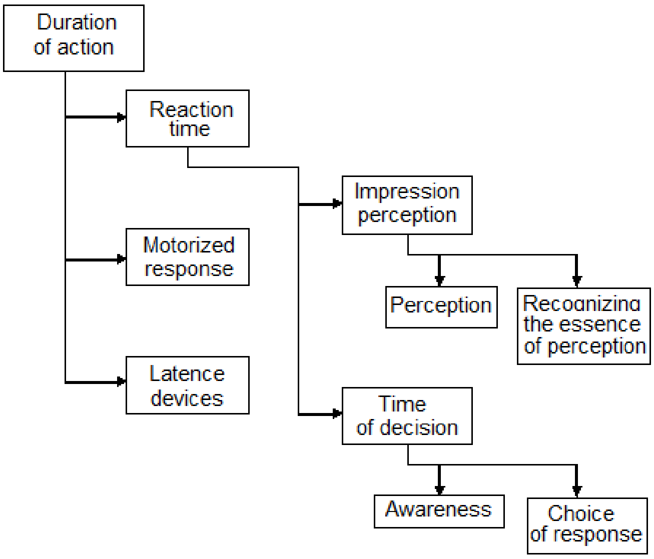


Fig. 7.3. Structure of the total duration of the action.

## 7.7 Reaction time

It represents a time that takes time from the moment the respondent registers the impulse that has occurred and decides on the response until the beginning of the response. This is the start-up phase of the whole process, consisting of the four subcategories listed below.

Perception: the time that is required for sensor sensing by sensor sensors. The factors determining perception detection and their actual influence on the reaction time value will be described extensively in the following chapter, however, there is a need to make a certain introduction to this topic. The character of the perception significantly affects the overall reaction time, the most important being the intensity of the stimulus, its complexity and the circumstances in which the stimulus is perceived, as well as the person's readiness for the stimulus to occur.

Recognition of perceptual nature: the time required to recognize the sense of perception. This component requires the application of information and experience from a person's memory to interpret the excitement coming into the sensory sensor. In some cases, there is an automatic answer, ie this section is very short. In these cases, of course, there are simple reactions, including unconditional reflexes. In other cases, this is a controlled response, which represents a disproportionately significant time. Generally speaking, a new subject, a stimulant, an unknown stimulus slows the reaction time, a less intense signal, and the uncertainty, whether the source of the stimulus, the specific moment of appearance of the stimulus or its form, and, of course, surprise. Undoubtedly there is a very close connection with the previous subcategory of perception, respectively. it is possible to conclude in many experiments the redundant character of subcategory recognition. However, its introduction brings a more complex theoretical basis of the problem of reaction time components. Last but not least, the results of the research justify inclusion in this theoretical framework.

Awareness: the time needed to recognize and interpret the nature of the environment, extract its meaning, and predict eventual development for the future. E.g. once the driver recognizes the pedestrian on the road and combines this perception with the knowledge of his own speed and distance, he will present a sequence of how and what will happen. As with the previous subcategory, the new stimulus slows down this phase, which is intelligently processed.

Choice of response: the time needed to decide what kind of response will be needed. Selection of possible reactions slows the reaction time if a more diverse set of possible signals exists.

## 7.8 Time to move

Once the response is selected, the subject must perform the required muscle movement. It is clear from the nature of the matter that the very beginning of the movement can be almost equal to the time of completion of the movement, especially in the simple reaction times. However, these cases are not very interesting for us. A more marked difference between the start of the reaction and the moment of completion of the reaction is observed for complex motor manifestations of behavior. For example, I can point out the situation in a confrontational struggle where the beginning of the reaction to effective defense is totally irrelevant, as the defense itself becomes effective only after the transition to a certain stage of the technique. Of course, there are a number of factors influencing the time required to perform the movement on this stage. In general, the more complex movement is required, the higher the latency.

## 7.9 Meaning of reaction time components in confrontational combat

The mandatory conditions of necessary defense in a clash, ie, the ability of the attacker to resist the attack by reacting, occur when the inequality of the success of the defensive action is fulfilled:

$$\Delta t_d < \Delta t_a ,$$

$\Delta t_d$ … duration of defensive action,

$\Delta t_a$ … duration of the offensive action.

The duration of the defensive action consists of two parts:

$$\Delta t_d = \Delta t_{rt} + \Delta t_m ,$$

$\Delta t_{rt}$ … the current response time of the defender,

$\Delta t_m$ … duration of the defense movement.

At the same time, the reaction time of the subject can be expressed by:

$$\Delta t_{rt} = \Delta t_p + \Delta t_r ,$$

$\Delta t_p$ … duration of perception:,

$\Delta t_r$ … duration of the decision-making process.

$$\Delta t_p + \Delta t_r + \Delta t_m < \Delta t_a .$$

There are several possibilities to increase the chances of effective defense:

- reducing the duration of the perception of the complaint,
- reducing the duration of the decision-making process,
- reducing the duration of the motor response.

Time requirements for individual components can be divided into three phases: visual perception, decision making and muscle movement. Approximately 70% of the total reaction time is the time required for visual perception, while 30% requires a motor response. This ratio refers to the transport driver's motor responses in the Demirarslana study 2008). Average division according to Bradáč (1997) is 28.4% for muscle movement, 71.6% for visual perception, respectively 23.8% to 76.2%. The proportion of perceived speed response increased as the driver followed another object, either within a range not exceeding five degrees from the perpendicular to the relevant object, respectively. exceeding this value. Of course, in the case of a struggle, there are more complex motor responses, thus balancing the two components.

Visual perception as a component of the reaction rate is influenced by the factors that will be discussed in the next chapter where the nature of the action will be explained. In general, the external environmental conditions, the spatial location of the subject towards the source, the direction from which the stimulus is exposed.

The time required for decision making is the most variable component of the reaction time. The factors that act on it can be very difficult to categorize in some way. It is clearly determined by the subject itself caused by the psychic states of the infected person, ie emotions, disturbance, inexperience in conflict struggle, etc. Therefore, the reduction of the duration of this phase may be mainly the experience gained in these situations, the psychological resistence.

The motor, movement speed determines the time required to perform a particular movement act, due in particular to the training of the muscular apparatus and to the speed of muscle contraction of the involved muscles. Trained subjects are therefore better placed to reduce the duration of this phase. These people have reached a stage called stereotype motion stabilization, where the movements are carried out accurately, fluently, in a coordinated way and economically. As a result, the time required for the motor response is greatly reduced, and the person is able to act precisely, thus increasing the chances of effective defense incomparably against the untrained. Another positive aspect in terms of effective defense is the fact that trained subjects generally gained the ability to perceive quickly in the trained area and, thanks to a stabilized dynamic stereotype, also reduce the time needed for decision-making. All these benefits of training contribute to a substantial reduction in the overall duration of the action.

However, many offensive actions can be made at short distances so quickly that they can not resist it. The attacker therefore detects the stimulus at maximum, but without relevant motor response it has no meaning in terms of its effective defense. Therefore, it is desirable not to react to the impulse that has already occurred, because it makes effective defense impossible. With regard to unarmed attacks, the easiest, fastest means to reach a criminal target in a violent way is to strike the limb, ie, the stroke, and the kick. The velocity of the strike itself does not play a significant role because it achieves the desired effect in the event of an appropriate attitude and the optimum distance from the injured person. The effectiveness of the strike also affects the correct pronation, respectively. forearm suppression and rotation and relocation of the hull. Similar motor operations are required when using a short cold weapon or heavy object strikes. However, the use of a short cold weapon is effective even with the movement of the limb itself. On the other hand, a stroke driven by just the movement of the limb would not be effective enough, but in both cases the initiation of motion and its detection as a stimulus for the injured would be less readable.

Therefore, if the attack action takes a considerably shorter duration than the duration of the defensive action challenged, its defense as a reaction to it is unrealistic. In order for it to be possible, it is essential that the attacker responds not to the beginning of the offensive action of his opponent, but to something that has been sufficiently prevented and helped to identify the stimulus itself. The attacker, then, anticipates the future development of his opponent's behavior, which he then acts on. In order to anticipate probable behavior, it also offers a solid opportunity to defend itself effectively. The determination of the components by the psychic and physical abilities of the subject subject was the subject of research by the already mentioned authors Olenika, Rožkova, Kargina (1984). We present the measured values according to the subject's preferred capabilities:

Tab. 7.1. Average group indicators of the development of psychic properties of top wrestlers with different ways of fighting.

| **Type** | **Simple reaction time (ms)** | **Complex motion reaction (ms)** | **Response to a moving object (ms)** | **Feel for time (s)** | **Rationality of operative thinking (number of moves)** |
|---|---|---|---|---|---|
| Player | 148,2 ± 10,2 | 200,9 ± 11,2 | 500 ± 190 | 3,87 ± 1,86 | 7,72 ± 0,41 |
| Stronger | 157,7 ± 11,3 | 224,9 ± 18,5 | 610 ± 220 | 4,93 ± 2,84 | 8,32 ± 0,71 |
| Tempaer | 160,1 ± 11,1 | 223,5 ± 24,1 | 690 ± 250 | 7,31 ± 4,20 | 8,42 ± 0,66 |

For illustration, we also attach the results of the measurements (see Table 2.3, 2.4 and 2.5) of Novák, Skoupý, Špička (1991) concerning this narrow issue. From the reaction times mentioned, it is obvious that the experimental person responds to something that prevents the opponent's leg from moving away from the pad. These measurements were performed in the gym during normal evening lighting. Measurement has confirmed that the level of illumination and its location greatly affect the ability of the test person to respond. With good illumination in the right direction, the simple reaction time on a non-standard signal, whose substrate is an offset followed by a kick, also gets negative values. The conventional start of the action takes the moment when the striker's leg has begun to move away from the pad. However, the last irreversible changes in the preparation of the trial person to carry out the follow-up action can be reliably identified under these conditions for 0.5–2 seconds before the determined start of the attacker's movement, which is sufficient for practical purposes.

Tab. 7.2. Conventional simple reaction time before selected combat actions.

| **Response type after exposure to a standard visual signal** | **Conventional simple reaction time (ms)** | |
|---|---|---|
| | **The shortest** | **Ordinary** |
| Press the button | 153 | 180-200 |
| Straight cast of the distant arm | 211 | 270-330 |
| Hook aside | 229 | 270-330 |
| External rotary key | 228 | 260-290 |
| An arc kick from a far farther foot from a combat guard | 220 | 240-280 |
| A circular kick from the bottom of the opponent's shin to the legs | 300 | 300-380 |
| Loss of battle guard to trace forward | 226 | 260-300 |
| Loss of combat prudence on track back | 210 | 260-280 |
| Cover from the front of the arm from the battle guard | 203 | 220-250 |
| Cover from top to front of arm from combat guard | 211 | 230-250 |
| Reverse the head | 211 | 230-260 |
| Bend your head aside | 201 | 230-280 |

Tab. 7.3. Conventional simple reaction time before selected combat actions.

| **Type of combat action** | **Duration of action (ms)** | |
|---|---|---|
| | **The shortest** | **Ordinary** |
| Direct hit | 91 | 120-150 |
| Hook aside | 120 | 130-150 |
| External rotary stroke without strain | 181 | 190-200 |
| The outer threshing of the distant arm from the combat guard | 139 | 150-170 |
| Top down from the battle guard through the forward arm | 105 | 110-120 |
| Direct the kick aside from the battle guard with the leg up to the knee | 241 | 270-290 |
| The end kick from the bottom of the opponent's shin | 143 | 150-160 |
| Arcing kick from the bottom of the battle guard to the far legs 90° | 277 | 300-320 |
| The swinging knob aside from a combat guard close to the legs to the waist | 334 | 350-370 |
| An outer kick from a combat guard over the legs to the waist | 345 | 360-380 |
| Seoi-nage from the distance from the front of the arm to the front | 467 | 550-590 |
| Placing over the calf (tai-otoši) | 441 | 500-550 |
| External impact (o-soto-gari) | 643 | 670-720 |
| Front thrust (uči-mata) | 338 | 470-560 |
| External cover (according to Šotokan school) | 159 | 180-190 |
| Indoor cover (according to Šotokan school) | 111 | 150-190 |
| Reverse the head | 100 | - |
| Bend your head aside | 110 | - |

Tab. 7.4. Duration of combat actions.

| **Experimental Person No. 2 performs:** | **Duration of simple Response Time of Experimental Person No. 1 (mean of measured values in ms)** |
|---|---|
| Lift forward + arch to the waist height | 48 |
| End kick from far farther leg | 62 |
| The end kick is closer to the leg | 93 |
| A kick from the bottom to the waist height | 88 |
| A kick from the front to the waist | 37 |
| Swing the kick aside from the front position to the waist height | 6 |
| Lift forward + arc kick from bottom to waist height | 115 |

## 7.10 Factors influencing the reaction time

Response time determinants can be classified according to a number of criteria, including alcohol, drug-stimulating drugs, and therapies that are relevant for both theory and practice. drugs, age, training, fatigue, spatial orientation to the stimulus, warning of incoming stimulus and tension. In the next, we were primarily interested in the question of changing the reaction time due to the level of alcohol.

Alcohol reduces the speed of information processes, simple, selective and recognition reaction times in experiments requiring a simple motor response in response. Last but not least, it also disrupts the cognitive abilities of the higher order, which is a prerequisite for the negative determination of complex motor responses,

## 7.11 Experimental part

The main objective of the experiment was to find human reaction times in an experiment focused on complex reaction time selective with a complex motor response. In addition to this goal, we focused on quantifying and expressing the reaction time dependency on the amount of ingested alcohol, preparedness due to the distraction of the subject and the intensity of the auditory stimulus. Another task was to express the time duration of the stroke from the rest position, both in the free space and the rigid body. On the contrary, the aim was not to follow the analysis of simple reaction times, whether with a complex motor response or with a simple type of motor response. Likewise, it seemed desirable, given the goals set, to configure the experiment so that the stimulus would characterize its randomness caused by spatial and temporal uncertainty during exposure.

Random stimulus signs for the purpose of this experiment: an impulse from a defined set of stimuli with which the subject was informed before the experiment began, each of which was the only correct response, the most important of which is the complex motor response, unlike the typical patterns used in the experimental psychology, there are no constant time intervals between stimuli, respectively almost constant intervals (Experimental psychology uses time intervals between impulses whose duration is in the range of about 500-3500 ms, which inevitably, at least in some cases, decreases the reaction time due to sequential effect), thus eliminating the so-called sequential effect ; In this experiment, on the other hand, we worked with time frames ranging from tens of milliseconds to more than a minute upper limit.

Also, an important factor for the randomness of the stimulus is the fact that there was a change in the character of the stimulus, ie there was an alternate exposure to the auditory stimulus (from the point of view of the complexity of the unimodal) with the audiovisual (in terms of bimodal complexity), and also accidentally participated in an undefined impulse, which the subject did not react at all. There has also been an ongoing substitution of the spatial location of the source of the stimulus, again in order to maintain the variability with respect to the subject.

The experiment was attended by 25 volunteers representing a group of very well trained people. The practical part of the research was carried out at the police gym of the Police Academy of the Czech Republic. Experiments and measurements for all volunteers lasted roughly 60 minutes. Because of the nature of the experiment, only a complex and simple reaction time was present that required a complex motor response.

The instructions were presented to the subjects before the start of the experiment. This was an outline of the focus of the experiment, ie the focus on the research of reaction times for a random stimulus that requires a complex motor reaction. In addition, the instructions consisted of defining the impulses, the kick, the kick, the back, the pulling of the pistol CZ vz. 75, abdomen, sed, light, crank.

It was explicitly stated that they should not respond to any further stimulus. Such instructions form the nature of a sample type experiment - the subject responds to stimuli, for which they must choose the right response and, in addition, to distinguish undesirable stimuli. If simple types were present, this was the way the subject performed a "neutral reaction, a simple move", and only modified the process to a correct response during the movement. In this case, I determined the value of the simple reaction velocity, and then the latency, which determines the time period from the start of the simple reaction to the actual reaction that is relevant to the given instruction. I am, of course, contemplating the overall reaction time, which I continue to work with in the context of the analysis of addictions.

Exposure to the sound of the conclusion was exclusively in the dorsal direction towards the subject. The criterion for selecting the suggestions made in the verbal expression was the requirement for a relatively equal duration of the instructions, which was also subject to the method of formulation of the assignment, the objective of which was not immediately obvious. Therefore, the subject received the appropriate instruction on the correct answers. In the case of more concise but significantly different signals in terms of length, it would be more likely to detect undefined signal, thereby obtaining the conditions for a simple reaction time, and in the course of its execution, the whole information would be expunged in the meantime, thereby " has specified "his / her response, ie he has made the required response. In other words, it could be said that the subject would be a signaling agent of the incoming stimulus, which is the exclusively positive determining factor of the reaction rate.

The alcohol level in the blood was measured with a breath alcohol detector - Alcohol Tester, however, to eliminate alcohol in the breathing body for about a while

He spent 10 minutes exercising to remove alcohol from his breath and speed up the absorption of alcohol in the blood.

## 7.12 Methods and results of data analysis

The very methods of data analysis were that I extracted the unchanged soundtrack in the best quality from the video I obtained. I analyzed the video in VirtualDubMod 1.5.10.2 build 2540. The record was used to determine the moment when the subject responded, which meant 40 ms accuracy due to the methods used in the video. With the interleaving cancellation function, a sequence of 20 ms was finally created, meaning this limit error in the output measurement. The input, ie the start of the stimulus exposure, the essence of which was the audio signal, was analyzed by Audacity 1.2.6, which was already working only with the audio track, for better accuracy and for the possibility of further analysis of the track, and made it easy to work on the timeline with resolution less than 1 ms, this sensitivity to the circumstances was optimal.

For each of the stimuli, I used a sound analysis that included the determination of the intensity of the auditory stimulus (expressed in dBFS units, the level of 0 dBFS corresponds to the maximum intensity), analysis of the frequency of the signal (frequency analysis) and its complete spectrum (spectrogram). Frequency analyzes and spectrograms do not, of course, be of primary importance in terms of the purpose of the work, but we consider their inclusion to be important in the complex processing of the given topic.

The average response time of all subjects at zero alcohol level was 395.27 ms (σ = 113.37). This value represents the mean of all values without resolution. For an unimodal audible stimulus of 0 dBFS, the average of all subjects was 342.65 ms.

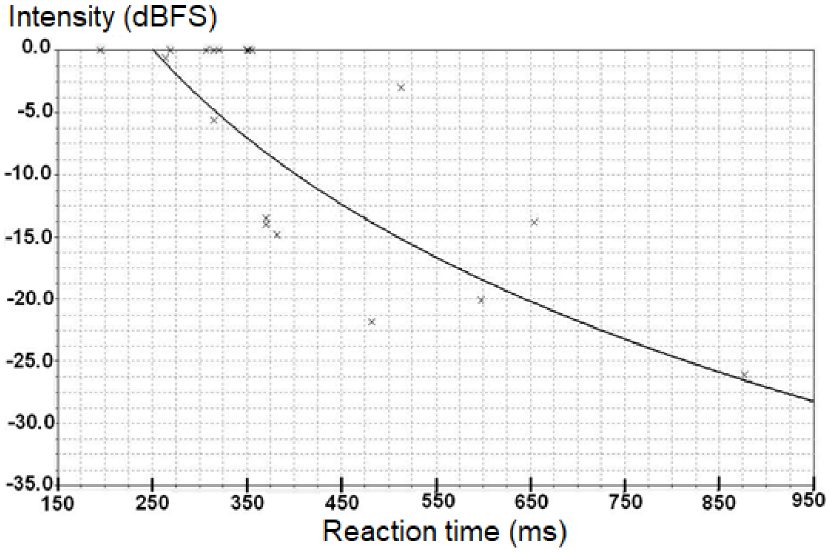


Fig. 7.4. Dependence of reaction time on the intensity of the auditory stimulus.

The nature of dependence is obvious - faster reaction times reach the subject if the stimulus gets higher and vice versa. Of course, the curve created from our measured values does not apply to stimuli that have not reached such intensity that they are detected. Such incentives did not occur in our experiment. It is obvious from the very essence that the value of the reaction time would not increase, respectively. did not diminish indefinitely, if the theoretical impetus was infinitely small, respectively. of great intensity. In the graph, such a circumstance would be represented by asymptotes, each of which would be parallel to the corresponding axis.

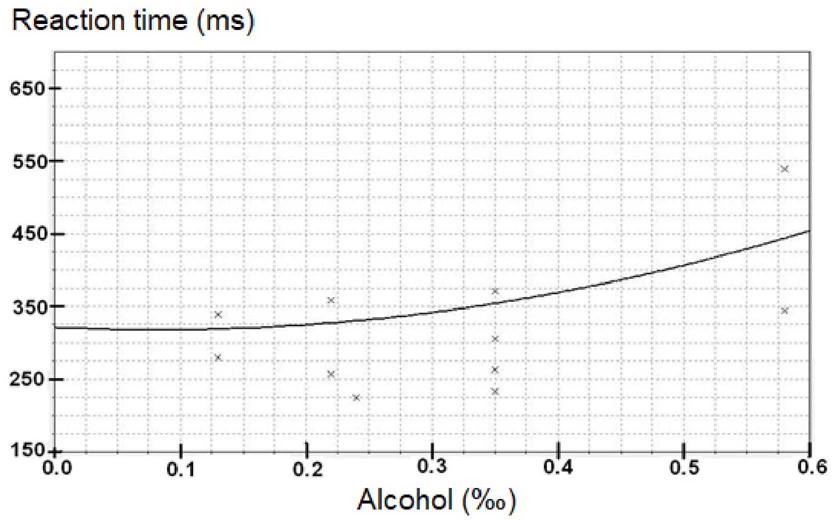


Fig. 7.5. Reaction time dependencies on alcohol level - maximum alcohol level of 0.6‰.

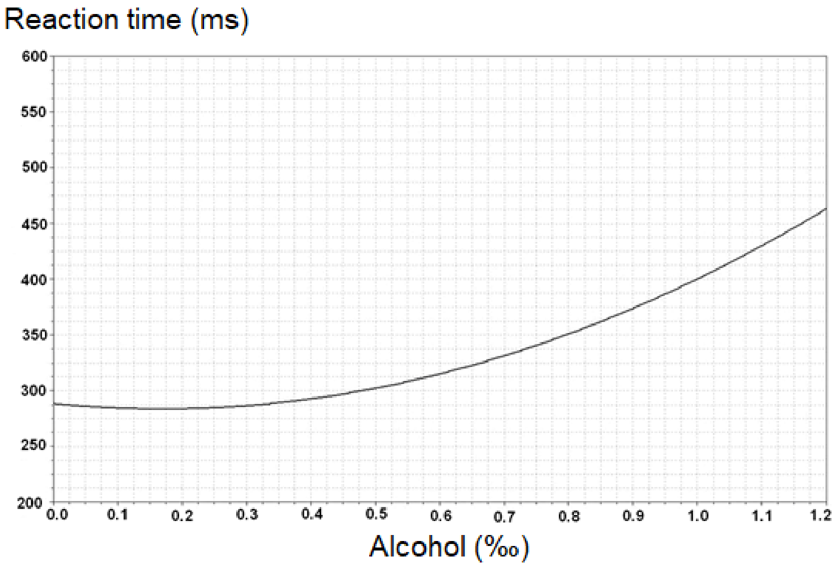


Fig. 7.6. Reaction time dependencies on alcohol level - maximum alcohol level of 1.2‰ (Straus, Danko 2009).

Analysis of the experimentally determined values indicates the excitatory effect of alcohol for very low blood alcohol levels, namely 0.17–0.23 g / kg.

The experiments and measurements carried out were performed only on a group of men, so it is not possible to say with certainty what specific values of reaction times women would achieve. Pilot research has shown the need to make the following steps in follow-up research: Performing multiple measurements from frontal positions vis-à-vis the subject, both with visual and audio-visual suggestions. The aim of this experiment would be to complete a set of reaction times for audio, visual, and audiovisual stimulation, which are the most important insights for expert research in the field. In all relevant areas of investigation, to obtain additional data to help clarify the dependencies and to clarify the reaction potential of the common population as well as to show the physiological boundary capabilities of highly trained subjects. To determine the effect of alcohol, it is necessary to further determine the influence of alcohol on the reaction capacity, to other components of the reaction capability. In addition, I consider it necessary to obtain reaction time values for higher levels of alcohol in the blood than approx. 0.6 ‰.

The hypothesis of reaction rate conditionality in response to stimulus intensity was confirmed. It was only an audio stimulus so far, but the sound stimulus responds most quickly to these types of stimuli. This has resulted in the best possible average response times, which will then be helpful in analyzing audiovisual stimulus responses, respectively. in the overall comprehensive assessment of human responsiveness from normal population or trained people.

Analysis of the effect of distraction on readiness and thus on the value of the reaction time confirmed the expectations and formed a determinant of a non-negligible character. The data obtained again provide a solid basis for examining the readiness and its impact on reaction time.

Interesting results have been obtained by analyzing the influence of alcohol on the reaction rate, where subjects were even excited on average at low levels, specifically at the level of alcohol in the blood, approx. 0.08‰. Subsequently, a negative determination occurred at approx. 0.4‰ and relatively high values. Analysis of the experimentally determined values indicates the excitatory effect of alcohol for very low levels of alcohol in the blood, for 0.17-0.23 g / kg. The graphs in Figures 9 and 10 show quite accurately the prediction of reaction time for a random stimulus requiring a complex motor response depending on the level of alcohol in the blood.

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# 8 Identification of person according to the dynamic skin stereotype

## Introduction

Walking is a fundamental locomotive activity of a man which is essentially significant for the quality of his life. The basic features of the motoric program are genetically conditioned and are further modified on the basis of individual characteristics of each person in the course of ontogenetic development. This locomotive activity includes many common features when being performed by different groups of people. On the other hand, it is possible to find a wide range of different "versions" with typical characteristics for a certain individual. The difference in the performance is associated with health, mental factors, external conditions (surface, shoes etc.) and, last but not least, also with biomechanical (anthropometric) parameters of the human body. Under normal conditions each man tries to walk in order to minimize energetic expenditure. Literature offers a wide range of walk definitions, some of them reflect factors that are necessary to be focused on while analyzing this locomotive activity.

- A manner of body movement from one place to another with alternate and repetitive change of the position of lower limbs on condition that at least one foot stays in the contact with the surface.
- The locomotion characteristic of the period of loading and non-loading of the limbs (Kirtley, 2006).
- Controlled fall during which the body falls forward from the stable position secured by a stance lower limb onto the other lower limb.
- The alternation of sequences of single and double support of lower limbs (Enoka, 1994).
- The repetition of a sequence of muscle-controlled movements in joints reoccurring for each limb that shift the body forward and keep its stability (Perry, 2004).

The issue of human locomotion, especially walking, has been addressed in many of our time by a number of authors. Attention was paid to a number of questions. In our observations, for example, a kinematic analysis of the locomotion was performed by, for example, Janura and Zahálka 2004, kinematic analysis of walking in selected groups of patients Janura et al. (2003), application of 3D videography in the analysis of gait-basic information (Janura et al., 2003), the gait analysis based on the measurement of ground reaction forces (Vaverka, Elfmark 2006).

The main terminological questions related to the possibilities of identification of persons according to the traces of human locomotion were then most prominent (Straus, Jonák 2006, Janura, Porada 2007, Janura, Zahálka, Porada 2007, Janura, Porada, Zahálka 2008, Janura, Porada 2009, Janura, Svoboda, Porada 2009). The definition (geit) of basic terms for criminalistical purposes was performed by Janura, Zahálka, Porada (2007) at the conference "Digital Forensic Forum Prague 2007" (Janura, Zahálka, Porada 2008, pp. 231–254).

# 8.1 Human locomotion (gait), basic terminology

## 8.1.1 Internal conditions for walking

There are two fundamental requirements for walking (Bronstein, 1996):

- *equilibrium* as an ability to occupy vertical posture and keep balance,
- *movement* as "an ability" to start and keep rhythmic step mechanism.

Many necessary conditions have to be fulfilled in order to assure these requirements. They are muscular tonus (adequate muscle force), presence of intact bone tissue, functioning joints, possibility of backward information (sight, vestibular apparatus, senso-kinetic system…) etc.

Walking at the same time requires the participation of all joints of the lower limb in the complex pattern of walking. The involvement of locomotive segments of the whole body requires movement control on high level. Therefore we can talk about walking only at the moment when a child shows control over individual parts of his/her body and is thus able to maintain a certain degree of dynamic balance (Trew and Everett, 1997).

## 8.1.2 Central mechanisms of walk control

Patterns of behavior, usually of a stereotyped character, that do not require conscious control and occur without the participation of cerebral cortex also include locomotion (Králíček 1995). The generator of the locomotive movement pattern is situated in the spinal cord, for each limb separately. In case all the limbs are involved in an activity, the activity of all the generators is mutually coordinated. Locomotion is not primarily of a reflective origin. Despite this, the afferent signalization from the limb proprioreceptors is very important. If it is eliminated, the cycle of locomotive movement is strongly altered and decelerated (Králíček 1995).

### Step cycle

In order to analyze a given locomotive activity of a cyclic character, i.e. also of walking, it is necessary to divide movement into basic parts that are repeated. The elementary unit of walking is a step cycle. A complete step cycle or stride is launched by the contact of a given part (usually by heel) of one foot with the surface and ends by another contact of the same part of the same foot. It is characterized as an interval during which a sequence of regularly repetitive parts of a given activity is realized (Gage 1991).

The division of the step cycle varies from author to author. The basic division however always talks about two main phases – *stance and swing phases:*

- Stance phase − part of a step cycle at which the foot is in contact with the surface,
- Swing phase − part of a step cycle at which the foot is in a supportless phase.

Their mutual ratio during the step cycle is at an average speed approximately 60:40 (Gage 1991; Rose and Gamble 1994). According to Sutherland (1994) 62% of the cycle is formed by the stance phase, 38% by the swing phase. The opposite limb falls, in the case of healthy people, approximately in 50% of the step cycle. In the course of the step cycle, a double support phase occurs twice, each of them taking 10% of the time of the step cycle.

In our case, we will use the division of the step cycle as stated by Perry (1992).

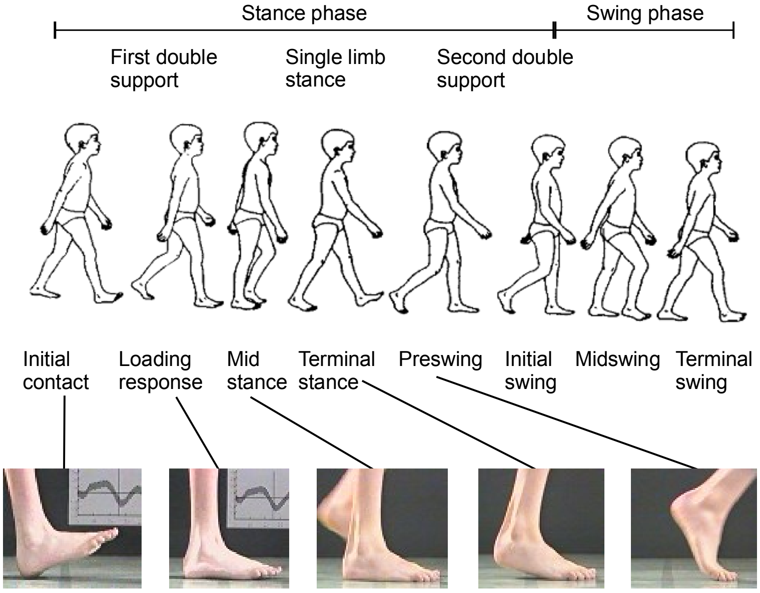


Fig. 8.1. Division of the step cycle to basic phases (adjusted according to Perry 1992).

Stance phase:

1. Initial contact; 0%
2. Loading response; 0–10%
3. Midstance; 10–30%
4. Terminal stance; 30–50%
5. Preswing; 50–60%

Swing phase:

1. Initial swing; 60–73%
2. Midswing; 73–87%
3. Terminal swing; 87–100% (Rose and Gamble 1994; Perry 1992).

Another frequently used division includes phases of the step cycle according to Vaughan (1992):

1. Heel strike
2. Foot flat
3. Midstance
4. Heel off
5. Toe off
6. Acceleration
7. Midswing
8. Deceleration

*Initial contact* (Rose and Gamble 1994; Dungl 2005)

Initial contact is a short-term activity that starts the stance phase. As in the case of normal (physiological) walking, a significant impact of ground reaction force takes place between the heel and the surface (Whittle 1997). Absorption of the stroke is enabled by the so-called "heel swing". It becomes the center of rotation around which tibia and foot segments movement. A knee joint starts to flex almost from full extension and the hip joint is in the flexion of about 35°. Concentric contraction of extensors of the hip (m. gluteus maximus, hamstrings) compensates the operation of the ground reaction force.

*Loading response phase*

Loading response refers to a period between the initial contact and opposite toe-off during which the loading is fully transmitted on the stance lower limb. The aim of this phase is to adapt to the increasing loading, stabilization of the pelvis and deceleration of the body movement. During "normal" walking the gravity force of the body is absorbed by means of 10–15° of flection in the knee joint. Concentric contraction m. gluteus maximus accelerates the body movement forward through the hip joint.

*Midstance*

Midstance is a phase of a step cycle which takes place between the toe-off of the opposite limb and homolateral heel-off. Its aim, from the point of view of biomechanics, is to stabilize the knee and to preserve the centre of mass over the support base. The so-called "ankle rocker" is a critical point for the movement as it enables the shift of the lower limb over the fixated foot. The centre of the rotation is transferred from the heel onto the centre of the ankle joint. Fluent completion of the movement requires unlimited dorsal flection in the ankle. Braking force appears primarily by means of m. soleus contraction. Under normal circumstances the whole plantar side of a foot remains in contact with the support surface during this phase.

*Terminal stance*

In the course of this phase the body is shifted forward before the fixated stance limb. The body movement forward creates a huge force moment causing dorsal flection in the ankle. The vector of the ground reaction force is shifted towards the little heads of metatarsi. This gives rise to an increased demand on the activity of plantar flexors still before the initial contact of the contralateral limb. The axis of rotation is moved onto the front part of a leg.

*Preswing phase*

The preswing phase is the terminal part of the stance phase. It begins in the contact (foot flat) of the contralateral limb and ends with the moment when the toe leaves the surface (toe-off). The body weight is transferred onto the contralateral limb. The ground reaction force is shifted behind the knee joint and together with m. triceps surae contraction enables flexion in the knee joint (normally 35–40°). It helps the toe-off and the shift of the limb in a forward direction. After the reduction of the take-off limb loading there is a quick decrease in the activity of plantar flexors. The hip flexion begins after the transfer of energy from shank to the area of the hip joint.

*Initial swing*

In this phase the movement of a thigh continues forward, flexion in the knee joint takes place and dorsal flexion in the ankle joint starts. Restriction of any of these functions requires the use of compensatory mechanisms (excessive body movement, pelvis rotation, increased flection in the knee joint etc.). During the physiological walking flexion and extension of the knee are passive at the swing, the limb operates as a simple pendulum.

*Midswing*

This phase begins at the moment of maximal flexion in the knee joint and finishes at the moment when tibia comes to the vertical position. It continues in the shift of a lower limb forward, the foot is not in contact with the surface. Further continuation of the movement needs extension in the knee and dorsal flexion in the ankle joint (Whittle 1997).

*Terminal swing*

The forward shift of a lower limb is completed by the extension in the knee joint to neutral position. The important thing is the deceleration of a thigh by means of excentric contraction of hamstrings and m. glutaeus maximus. In consequence of m. tibialis anterior contraction ankle joint is found in a neutral position.

### 8.1.3 Joint and muscle activity during stance phase

*Hip joint (Figure 8.2)*

Movements on the sagittal plane are simple and can be shown by means of sinusoid. Maximum flexion in a hip takes place during the terminal swing phase, there is a slight extension shortly before foot flat. Maximum extension occurs at the impact of a contralateral limb. After this contact flexion in the hip joint is started on the “back” limb.

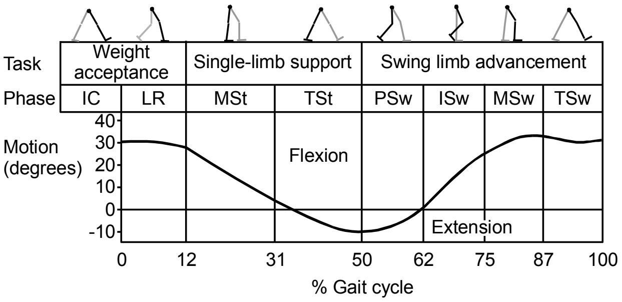


Fig. 8.2. Change of an angle in the hip joint in the course of a step cycle (adjusted according to Perry 2004).

*Legend (Figs. 2–4):*
*IC – initial contact*
*LR – loading response*
*MSt – midstance*
*TSt – terminal stance*
*PSw – preswing*
*ISw – initial swing švih*
*MSw – midswing*
*TSw – terminal swing*

*Knee joint (Figure 8.3)*

The first flexion wave begins after the foot flat with the surface. It serves for the absorption of the impact as well as for an effective shortening of the limb length. The second flexion wave is necessary for the toe off at the beginning of the swing phase. Flexion in the knee is, in this case, started at the end of the single-support phase when the heel starts to rise from the surface. Maximum flexion takes place in the swing phase at the moment when the limb passes the other (stance) limb. As a result of flexion, there is an effective shortening of the lower limb. This helps to the maintenance of the foot of the swing limb in the air. It is followed by a quick extension with maximum value before the contact of the foot.

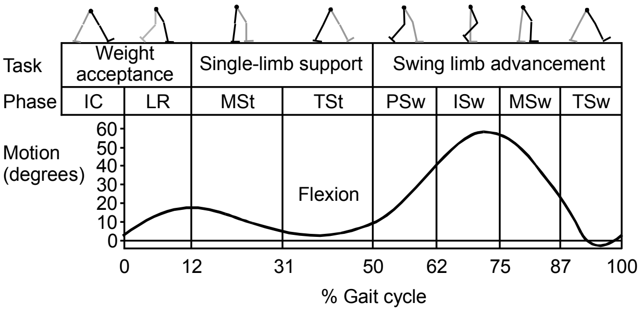


Fig. 8.3. Change of an angle in the knee joint in the course of a step cycle (adjusted according to Perry 2004).

*Ankle joint (Figure 8.4)*

After the initial contact there is the plantar flexion that influences the movement of the front part of the leg towards the surface. In the course of the midstance phase, the tibia shifts forward. The movement in the ankle joint is characteristic of dorsal flexion. Before the initial contact of the contra-lateral limb, there is a significant plantar flexion that lasts until the toe-off. In the course of a swing phase, the ankle moves back to dorsal flexion, the position is nearly neutral. This position lasts until the beginning of another initial contact. The kinematic of the ankle joint is usually characterized as “three rockers in the ankle joint”.

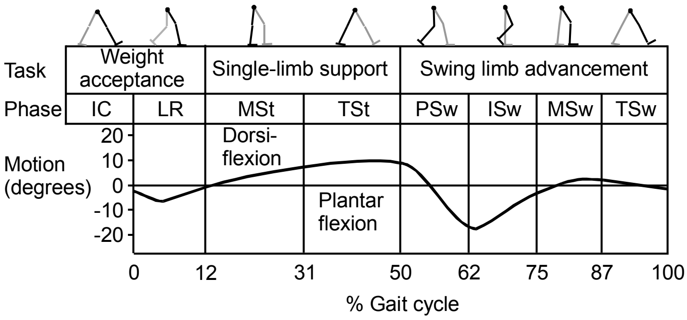


Fig. 8.4. Change of an angle in the ankle joint in the course of a step cycle (adjusted according to Perry 2004).

*Note:* The movement of the upper limbs when walking has an important meaning primarily from the point of view of the possibility of maintaining dynamic equilibrium. Therefore, there is the possibility of movement with a great extent in the sagittal as well as frontal level despite a relatively low mass of segments of upper limbs. Although the influence of the movement of the upper limbs on walking is indisputable, there is only a minimum of outputs in case of healthy individuals that would deal with this issue in detail. The main reasons for the “lowered” interest in the movement of upper limbs can be great variability of the activity that is so typical of it. Another reason is a smaller influence on the overall position of the body (body center of mass) that is related to the weight of the upper limbs.

## 8.1.4 Movement of the center of mass (COM) during walking

At “normal” walking, a trajectory of the center of mass is in the shape of a sinusoid. The total extent of the vertical shift is at a normal speed of walking of adults about 5 cm. The maximum height is reached approximately in the middle of the midstance phase when the opposite limb is found in the middle of the midswing phase. The center of mass drops to its lowest position in the course of double support while both feet are in contact with the surface. The extent of the vertical deviation is influenced by the movement of individual segments. To minimize it, the declination of the pelvis, rotation towards swing lower limb and flexion in the knee joint of a stance lower limb are used (Inman et al., 1994). Soderberg (1997), Trew and Everett (1997) evaluate the range of the vertical oscillation of the center of mass as a criterion for the determination of economy of walking. The extent of the deviation depends on the step length; it tends to increase with the speed of walking. Center of mass at the same time moves in the medio-lateral direction, its movement can also be described by means of a sinusoid.

The position of the center of mass influences the distribution of pressures on the contact of the foot with the surface. This distribution is characterized by a weighted mean of all the pressures operating on the surface of contact planes – center of pressure (COP). During walking, COP moves on the trajectory from the heel through lateral part of a sole to its center, then to little heads of the first two metatarsi and finishes at the last phalanx of the big toe (Whittle 1997). This trajectory is prone to great variability, even in the case of healthy individuals.

### Analysis of the movement

Analysis of the locomotive activity can be carried out on various levels that are dependent on the aims of the analysis and on the technical conditions of the workplace. When doing qualitative analysis we describe and assess movement without measuring concrete physical quantities. It is primarily the professional level of the assessors which plays a very important role, their experience and knowledge about the monitored movement. Smaller demands are placed on technical and device equipment. A typical example of this way of measuring is the visual assessment of a real movement or its record. Although qualitative analysis brings many very important pieces of knowledge and its results are often the only information about the given activity, it doesn't enable us to precisely define (quantify) the size of the output quantities.

In this case, it is necessary to use quantitative methods for the analysis of movement whose output includes numeric values (these usually state the extent of the physical quantities). To obtain them it is necessary to have corresponding material equipment that enables own measurement with the least possible room for error.

The basic division of quantitative methods in biomechanics stems from the character of the measured quantity. If force is the measured parameter, we call these methods dynamic. In the case that we monitor movement with no regard to cause (forces) that bring it about, we find ourselves in the area of kinematic methods. We can derive other quantities from basic parameters – trajectory and angle – and their dependence.

### Body center of mass, segments center of mass

The body movement is marked out by great complexity that is conditioned by a relatively high number of elements (segments) organized to a kinematic chain and various characteristics of tissues from which the body is formed. To determine selected parameters of a piece of locomotive activity that are related to the whole body (body trajectory in the course of movement, body speed at the moment of toe-off and foot flat etc.), it is worth making certain simplifications. This means that we replace the human body by one mass point – by the body center of mass (by the point of application of the gravity force).

*Note:* Regarding the above mentioned data the determination of the center of mass is burdened by a mistake that is multiplied in such cases when it is not possible to state the precise position of individual segments.

When determining the centre of mass we replace individual segments by solids with no regard to the kind and number of tissues of which they consist. The determination of the number of segments is done according to the type of a task. A 14-segment model is most frequently used (head, neck, body and pair segments – upper arm, forearm, hand, thigh, shank, leg). As they are the primary internal organs that cause differences in the qualities of individual parts of a trunk, this segment is usually further divided to e.g. upper, middle and lower part (Figure 8.5).

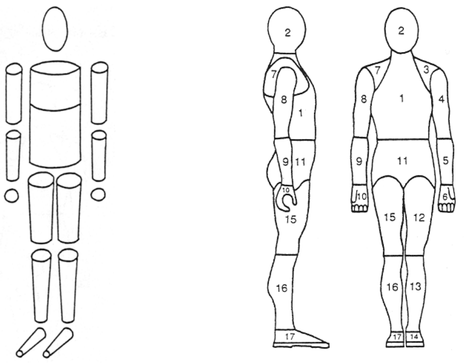


Fig. 8.5. Human body model (Hanavan, 1964), hominoid (Hatze, 1980).

When determining the body center of mass we make use of the centre of mass of its segments from which the body model is created for a given locomotive activity. The center of mass of individual segments usually lies on their axis; on the vector with outer points in the centres of joints enclosing segments. As for shank, leg and hand the segment it is divided by the center of mass in the ratio of 2:3 (smaller part is at the proximal end of the segment); for upper arm, forearm and thigh this ratio is 4:5. These values correspond to the percentage formulation stated by Karas et al. (1990) (Figure 8.6).

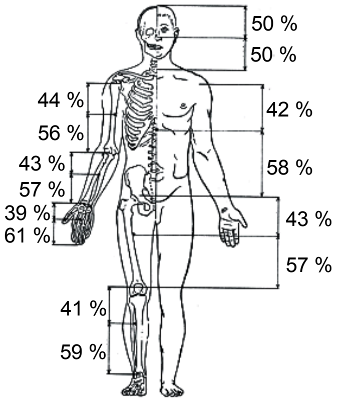


Fig. 8.6. Percentage formulation of the position of the human body segments' centers of mass (Karas et al., 1990).

To determine the body center of mass we most frequently use an analytical method that enables us to use algorithms usable for a wide range of locomotive activities. It can be thus applied also during kinematic analysis of movement by means of videography.

When determining the center of mass we start from the following consideration (we assume the use of the n-segment model):

1. The sum of the weights of individual segments equals the total body weight.

$$m_1 + m_2 + ... + m_n = m$$

2. The sum of gravity forces that affect the segments equals gravity force affecting the whole body. $G_1 + G_2 + ... + G_n = G$

The sum of the moments of gravity forces (regarding the given point; usually the beginning of the reference frame where we put the record of the locomotive activity) that affect individual segments equals the total moment of the gravity force.

$$M_{G1} + M_{G2} + ... + M_{Gn} = M_G$$

We get the following formula for the x axis:

$$m_1.g.x_{T1} + m_2.g.x_{T2} + ... + m_{14}.g.x_{Tn} = m.g.x_T ,$$

where m – total body weight (100%); g – acceleration of gravity (g = 9,81 $m.s^{-2}$); $m_1$, $m_2$, ..., $m_n$ – relative weight of the segments; $x_{T1}$, $x_{T2}$, ..., $x_{Tn}$ – x-coordinates of partial centers of mass; $x_T$ – x coordinate of the general center of mass.

For the coordinates of the general center of mass that is established by means of n segments, we get:

$$x_T = \frac{\sum_{i=1}^{n} x_{Ti}.m_i}{\sum_{i=1}^{n} m_i}, \; y_T = \frac{\sum_{i=1}^{n} y_{Ti}.m_i}{\sum_{i=1}^{n} m_i}, \; z_T = \frac{\sum_{i=1}^{n} z_{Ti}.m_i}{\sum_{i=1}^{n} m_i},$$

where $x_{Ti}$, $y_{Ti}$, $z_{Ti}$ – coordinates of the partial center of mass of the i-segment, $m_i$ – relative weight of the i-segment.

**Relative weight of segments**

As in the case of the analysis, we usually work with the data of a person with whom there hasn't been real contact, we use a relative value to determine the weight of individual segments. It is the weight of the segment expressed with regard to the total body weight (Table 8.1).

Table 8.1. Relative weight of segments (Karas et al. 1990).

| *Segment* | *Sušanka (1980)* | *Range of published values* |
|---|---|---|
| Head | 0.074 | 0.0568–0.0886 |
| Trunk | 0.448 | 0.4028–0.5070 |
| Thigh | 0.124 | 0.0970–0.1473 |
| Calm | 0.046 | 0.0399–0.0530 |
| Foot | 0.016 | 0.0114–0.0210 |
| Upper arm | 0.029 | 0.0259–0.0336 |
| Lower arm | 0.017 | 0.0153–0.0228 |
| Hand | 0.007 | 0.0054–0.0100 |

### 8.1.5 Analysis of walking

Walking is marked out by “regular” multiple repetitions of movements of body segments, step by step. As a result of this, the description of walking talks usually about what happens in the course of a one step cycle, assuming that the following step cycles are all the same. In this case it is the so-called rational approximation that is conditioned by a difficult analysis of movement taking place in a greater space. Nevertheless, we have to take great variability that can occur among different individuals into account or with one and the same individual (Smidt, 1990).

Elementary spatio-temporal parameters of a step cycle (Figure 7.7) can be found while using procedures that do not require complicated measuring devices. This group of characteristics usually includes:

*Cadence* is defined by the number of steps in a standard time unit (number of steps/min).

*Step length* is given by the distance between the same points on both feet (usually between heels) in the double support phase.

*Stride length* is defined by the distance between two successive foot contacts of one and the same leg.

*Walking base* is the distance between feet, usually measured from the heel centers.

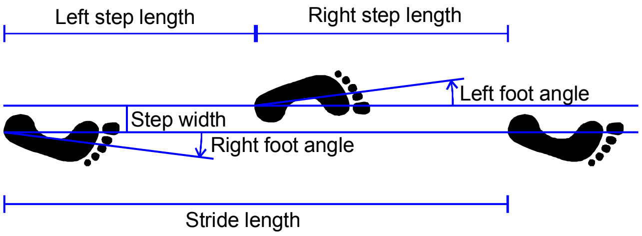


Fig. 8.7. Graphic illustration of basic spatio-temporal parameters of the step cycle.

The relative simplicity of measuring these parameters does not downgrade them. However, it has a limited testifying value. It doesn’t inform us about the position of the segments in the kinematic chain or the magnitude of the affecting forces.

The objective and complex assessment of locomotive activities, including walking, requires simultaneous use of more methods that serve for the determination of basic kinematic and dynamic parameters completed by electromyographic examination of the muscle activity.

### 8.1.6 Kinematic analysis of walking

Videography is the most frequently used kinematic method that is based on the analysis of the movement of important points, selected segments or the whole body by means of the evaluation of the video record. Marking the points on the record of the locomotive activity (on the human body) leads to the obtaining of plane coordinates that are used to determine elementary kinematic quantities (trajectory, angle, speed, angular speed …).

This process is valid if the monitored movement takes place on a level that is perpendicular to the optical axis of the video camera. In all other cases, the calculation can be made but the obtained values are biased depending on the size of segments in turning. In practice, the movement that takes place on one plane is, nevertheless, quite exceptional.

When transferring from plane to spatial representation, we have to broaden the plane system of coordinates. This means that we add third z axis to the original x, y axes. Any point is, in this case, represented by three coordinates that unequivocally state its position – during free movement in space the point has three degrees of freedom.

Let’s have points A, B, C with the coordinates A = [$x_A$; $y_A$; $z_A$], B = [$x_B$; $y_B$; $z_B$], C = [$x_C$; $y_C$; $z_C$]. For the AB abscissa (distance between A, B points; length of segments defined by A, B points) the following is applied:

$$v(A, B) = |AB| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}.$$

The size of the $\alpha$ angle between segments is derived from the relation:

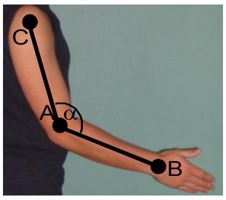
$$\cos\alpha = \left| \frac{u_1 \cdot v_1 + u_2 \cdot v_2 + u_3 \cdot v_3}{|\mathbf{u}| \cdot |\mathbf{v}|} \right|,$$

$$\text{kde } \mathbf{u} = B - A = (u_1; u_2; u_3) = (x_B - x_A; y_B - y_A; z_B - z_A)$$

$$\mathbf{v} = C - A = (v_1; v_2; v_3) = (x_C - x_A; y_C - y_A; z_C - z_A)$$

$$|\mathbf{u}| = \sqrt{(x_B - x_A)^2 + (y_B - y_A)^2 + (z_B - z_A)^2}$$

$$|\mathbf{v}| = \sqrt{(x_C - x_A)^2 + (y_C - y_A)^2 + (z_C - z_A)^2}$$



When using video record, every three-dimensional (3D, spatial) object, including the human body is shown as a two-dimensional (2D, plane) figure. Thus, when using one recording device and when marking points on the record from this video camera we can obtain only 2D coordinates. This goes for every record of a given movement from any video camera. Marking the same point in the same position (corresponding by recordings) on different records gives us several pairs of plane coordinates of this point. We can create spatial coordinates of the point by their assembling – transformation. It is therefore necessary to use a record from at least two video cameras for the spatial analysis of movement (Figure 8.8).

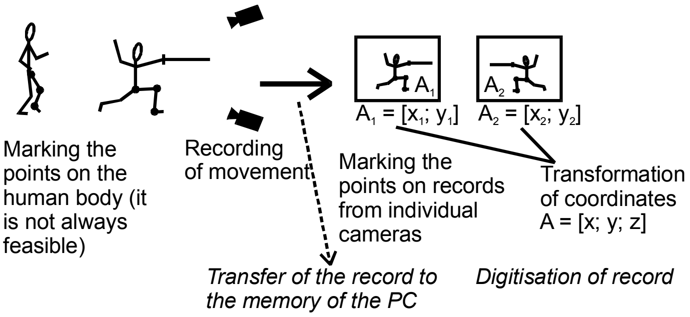


Fig. 8.8. Schematic representation of basic input steps when analyzing movement using 3D videography.

Marking selected points that serve for e.g. the representation of individual segments has to be completed by other parameters. It is necessary to supply the given software with “other pieces of information” about the position of individual segments. In each recording, we will therefore mark another point (orientation, referential) that is the same for all the recordings on the record from the given video camera. This enables us to create a sequence of analyzed pictures.

Knowing the coordinates of monitored points helps determine basic length parameters (segment length, step length etc). What is, though, the measure of this quantity? In what unit of measure is the length given? To transfer these units (pixels) to commonly used length units we have to evaluate the measure. The measure is a formation (plane for 2D analysis, spatial for 3D analysis) whose proportions we know. We place the measure to selected positions so that it enclosed a plane (space) in which analysis takes place. Marking the points on the measure that define the abscissas of a known size gives us values for the transfer to real length units. Elementary areas in the movement analysis by means of evaluation are shown in Figure 8.9.

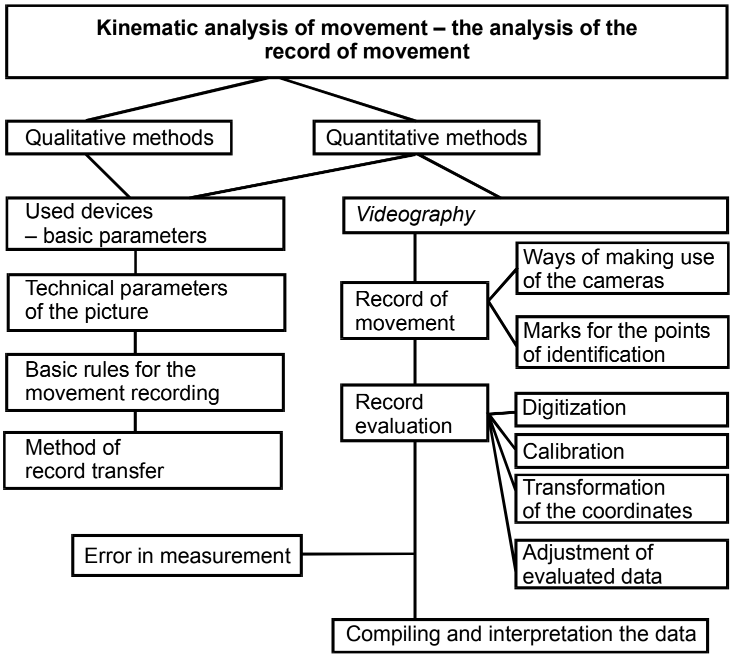


Fig. 8.9. The scheme of key areas and elementary steps in the movement analysis by means of the evaluation of a video record.

## 8.1.7 Location of cameras

The location of cameras in case of spatial analysis depends on the type of the dealt-with task and possibilities of a workplace as to the number of used devices. As the fundamental prerequisite for 3D analysis, we find the visibility of every evaluated point on the records from a minimum of two video cameras, this criterion is critical for the location of video cameras. If we can keep this rule similarly with different positions of video cameras, we choose such a location when the angle between the optical axes of individual devices approaches 90°.

To analyze movement that is marked out by great extent, we use video cameras that "watch" the recorded object by means of their own movement. The size of the angle that characterizes the shift (rotation) of the video camera must be given and recorded in every moment. The movement record by means of rotating video cameras and its processing is more complicated and requires the use of a special device.

## 8.1.8 Marks for the identification of selected points

To increase the quality of evaluated data and to accelerate the process of assessing the record, it is necessary to designate selected points on the monitored object.

*Placing the markers on the human body*

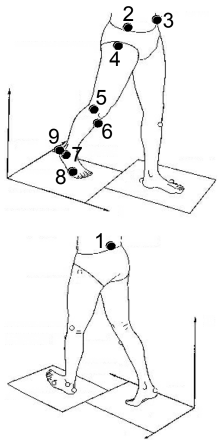
Individual segments are defined through selected anatomic points. When analyzing the video record we do not work with these points. However, we work with their projection on the skin. In the first phase it is necessary to make palpation of the appropriate anatomic point and reproduce this point on the body surface. During this activity problems can occur relating to e.g. the amount of subcutaneous fat that inhibit palpation of the given point and increase the danger of defect.

For the evaluation itself, the markers shouldn't be placed collinearly (in one straight line) so that reproduction of a segment by means of a plane figure (e.g. triangle) moving in the space could take place. This position of markers is important from the point of view of the possibility of subsequent determination of rotation of the segment with regard to its longitudinal axis.

The main problem that is associated with the definition of segments by means of surface markers is the shift of these markers in the duration of the movement. Soft tissues that are found between the bone and the sign movement owing to the speed changes and inertia. This is the cause of the position change of the sign in respect to the point on the bone. The value of these changes cannot be clearly stated as the somatic parameters of individuals are not the same (layer width, tissue distribution…). To eliminate these defects or to decrease negative effects, special algorithms are used. Their use is quite complicated.

*Sets of markers used for the analysis of walking*

An example of the set of markers that is typical of the designation of lower limbs when walking is a set named according to the place of its origin as Helen Hayes Hospital (Figure 8.10).



Legenda:
1 – os sacrum
2, 3 – spina iliaca anterior superior
4 – trochanter major femoris
5 – epicondylus lateralis
6 – tuberositas tibia
7 – malleolus lateralis
8 – caput ossis metatarsi V.
9 – heel

Fig. 8.10. Marking of segments when analyzing walking – modified set of Helen Hayes Hospital markers.

If we want to make a complex kinematic analysis of walking, it is necessary to work with the whole body, i.e. to mark and assess points also on other segments. In some cases we can encounter deviations in the selection of points that, nevertheless, shouldn't have a significant meaning for the values of output parameters. The location of the markers is influenced by the character of the given task and conditions of the measuring (tested person, environment, measuring device). The representation of most frequently used points that serve for the analysis of the body movement is shown on the Figure 8.11.

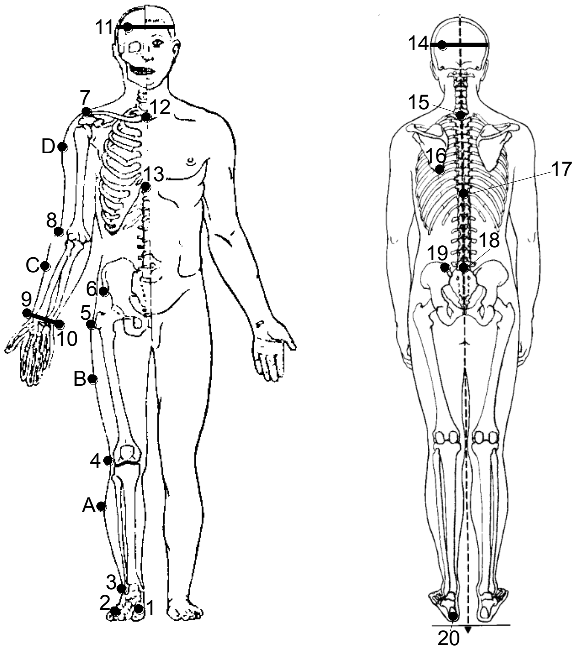


Fig. 8.11. Location of points on the human body in the kinematic analysis of walking.

*Legend:*

*1. caput ossis metatarsi I*
*2. caput ossis metatarsi V*
*3. malleolus lateralis*
*4. epicondylus lateralis femoris*
*5. trochanter femoris major*
*6. spina iliaca anterior inferior*
*7. acromion*
*8. epicondylus lateralis humeri*
*9., 10. points on the elastic tape for marking the wrist*
*11. point on the elastic tape to mark the head (usually two from the front view)*
*12. processus xiphoideus*

*13. incisura jugularis*
*14. point on the elastic tape to mark the head (usually two from the rear view)*
*15. processus spinosus C7*
*16. angulos inferior*
*17. processus spinosus Th10*
*18. processus spinosus L5*
*19. spina iliaca posterior superior*
*20. os calcaneus*
*A, B, C, D – points for marking the shank, thigh, forearm and upper arm (their position isn't strictly defined; it mustn't lie on the straight line with other points determining a given segment).*

The markers on the body surface (projection of anatomic structures) are only an auxiliary device for the subsequent analysis. They serve not only to define segments but also as input information for the determination of joints centers etc. Theoretical apparatus to this area can be found e.g. in the works of authors Dempster (1955), Zatsiorsky (1998). Mathematical solution is a part of some software that is used for the analysis of the movement record.

It is necessary to realize that the marking of the points on the human body can be made only in case of laboratory measuring or limitedly in the field of measuring. There are, however, many situations when it is not possible to locate the points (movement record during sport, record analysis from industrial cameras etc.). In this case we work with the "estimation" of the points that increases the risk of the error occurring. It has already been shown in the basic parameters (trajectory, angle) and significantly rises when deducing other quantities (speed, acceleration) through derivation.

*Synchronization of video cameras (of records)*

To obtain spatial coordinates of a point, it is necessary to know a minimum of two pairs of plane coordinates of this point in a certain moment. Therefore, it is essential to synchronize the records from various devices so that there was no time shift between the beginnings of individual fields (the first, second ones etc.). This condition is fulfilled e.g. by the use of a mode genlock. Its main advantage lies in the fact that we can use a conventional video-signal that serves as a signal for synchronization.

*Calibration*

Calibration in the analysis of the movement record is one of the main steps needed to determine dependencies between real extents and corresponding data gained on the record.

Calibration involves:

1. Determination of coordinates of known points in the space (points whose distance is strictly defined) that are required for the measure between real and image system of coordinates – calibration of space.
2. Finding the deviations of coordinates of evaluated points from their real coordinates that show us the influence of used devices on the quality of assessed data – video camera calibration.

### *Types of calibration devices*

There exist various pieces of apparatus that can be used for calibration and that differ primarily in size, number and shapes of points intended for calibration and their location. Calibration frames can be divided to several groups:

1. Poles, rods and chains that are hung from the ceiling, or fixed in the tripod on the surface.
2. Strong frames (most often cube, block) formed from solid elements that are used primarily in laboratory conditions.
3. Folding frames that are formed from solid elements, tight ropes, cables etc.

### *Coordinates transformation*

The transformation of coordinates is a process in which the plane image coordinates are transferred to real spatial coordinates of a point. It is a procedure in which the plane coordinates of the point that we get by its designation on the PC monitor are combined with plane coordinates of the same point caught on the record of a different video camera.

The most widely used procedure that serves for the coordinates transformation is nowadays the so-called Direct Linear Transformation, DLT, which was first presented by Abdel-Aziz and Karara (1971).

### *Adjustment of evaluated data*

Data gained through the videography method is influenced by many factors. Some of it can be removed by conscientious preparation for measuring; others are connected to the level of the measuring technique. Their effect cannot be eliminated, not even when maintaining the basic methodological rules. The procedure that enables the elimination or reduction of disruptive factors from the evaluated (raw) data is called smoothing.

The main techniques for smoothing raw data include polynomial regression, interpolation with the use of splines and the elimination of signal components that are caused by disruptive effects of individual factors in the process of measuring – digital filtering.

### *Quality of evaluated data*

In common practice as well as when using the latest a device, the measured value differs from the real size. The number of disruptive factors that we see in the course of the movement recording, its processing and evaluation is relatively high.

We can use three categories to state the elementary characteristics of systems and data obtained by means of these systems:

- accuracy – difference between the measured and real (true) value,
- precision – expressed by means of a variance,
- resolution.

Precision informs us about the method quality while accuracy relates to the result quality. The use of the described procedures cannot replace data gained by means of RTG, magnetic resonance etc. Integrated methodology however enables us to compare results among various profession groups or realize the longitudinal observation of selected individuals.

### 8.1.9 Dynamic movement analysis

Dynamic movement analysis uses force parameters measuring (inner x outer forces) for the quantification of a locomotive activity. To state the selected dependencies, it is necessary to focus on the force changes in the course of a given activity, i.e. to determine dependence of force on time (F(t)), that is an output when using dynamography.

The essential device equipment that is used for the determination of this dependence includes force platforms. These devices use for the movement analysis the measuring of a ground reaction force that appears during the contact of the human body with the platform surface. The resulting ground reaction force is distributed to three basic components in the anterior-posterior, medio-lateral and vertical direction (Figure 7.12). This dissociation enables us to quantify not only the vertical element that is usually dominant in the walking period, yet also the magnitude of shear forces characterizing the foot loading in the deceleration and acceleration phase of the stance phase (Figure 8.13). The force and time parameters enable to determine the force impulse (I).

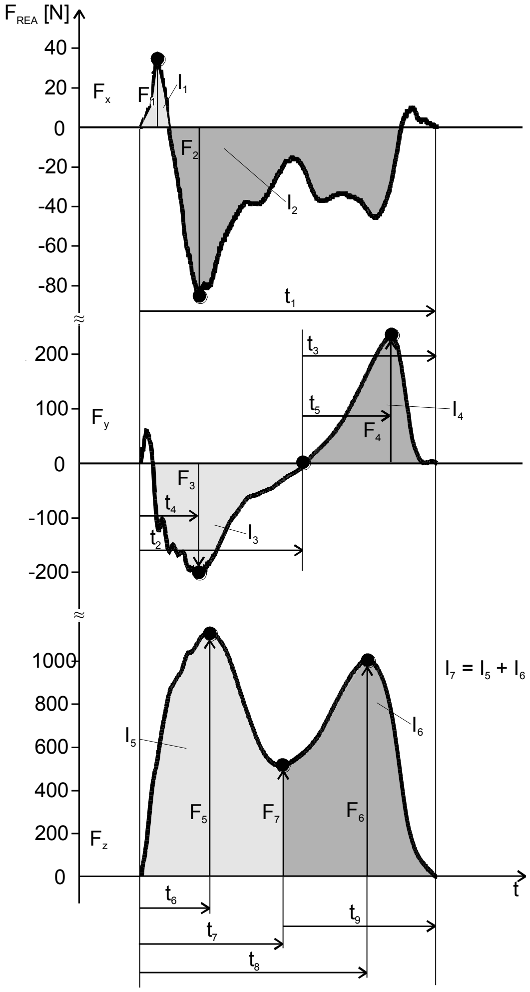


Fig. 8.12. Graphic representation of the medio-lateral (Fx), anterior-posterior (Fy) and vertical (Fz) components of the ground reaction force and measured parameters during the stance phase (Vaverka and Elfmark 2006).

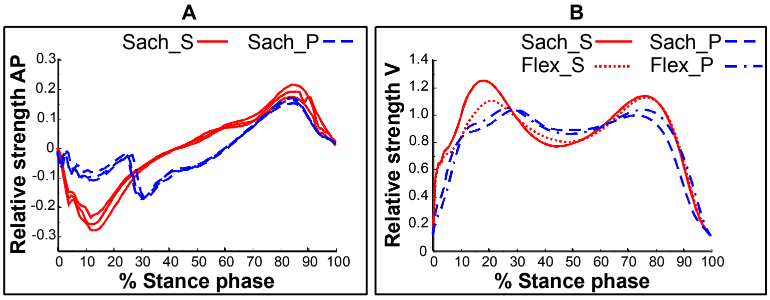


Fig. 8.13. Graphic representation of the anterior-posterior component of a ground reaction force on a sound and prosthetic limb when walking with conventional prosthetic foot (A). Graphic representation of the vertical component of a ground reaction force on a sound and prosthetic limb when walking with conventional (Sach) and dynamic (Flex) prosthetic foot (B).

Measuring the ground reaction force is only one part of the information about the dynamics of the movement. To determine the force impact it is necessary to know its magnitude but also distance from the rotation point. This rotation point is most often represented by joint centers* in the human body. The product of the force magnitude and its distance from the rotation point (force arm) gives us the moment that characterizes the magnitude of the rotating force effect.

**Note:* There is a certain extent of simplification as the rotation center changes in the course of the movement in the joint.

During walking, the position of the ground reaction force vector changes with regard to the given joint several times during the step cycle. A small difference in the position of the force vector can thus cause an essential change in its impact – opposite orientation of moment (dorsal and plantar flexion in the heel joint, flexion and extension in the knee joint etc., Figure 8.14).

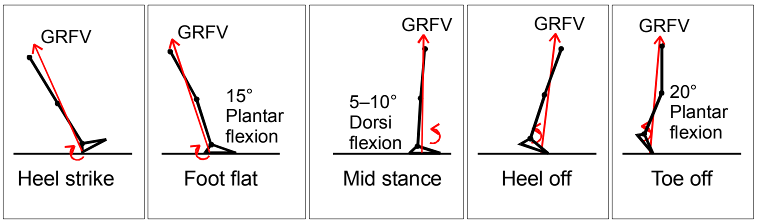


Fig. 8.14. The course of the ground reaction force vector and the effect of the ground reaction force moment during a step (adjusted according to Kirtley, 2006).

To evaluate the foot contact we usually use the determination of the magnitude and distribution of pressures that can predict danger places in the sole of the foot. E.g. the Footscan system works with the platform of 2070 × 460 × 20 mm with the measuring area of 1952 × 325 mm. Under the cover layer there are 16,384 sensors (4 per cm$^2$). The sensitivity of the sensors ranges from 0.7–155 N.cm$^{-2}$ according to the software employed. Outputs can be made in different variations, from analysis of loading of the whole foot through its division to individual parts to the evaluation of the selected areas (Figure 8.15).

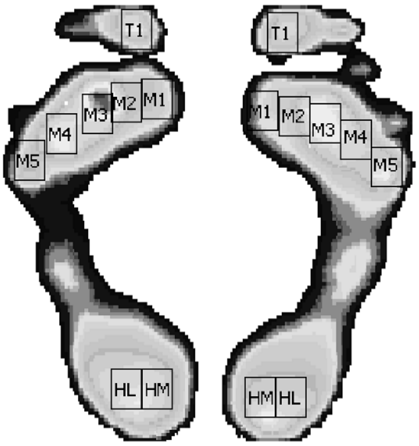


Fig. 8.15. Representation of selected areas of the foot when assessing pressure during stance phase.

Figure 8.16 shows the comparison of left and right foot flat when walking in the case of a top sportsman who intensely uses left foot as the taking-off one. An important indicator of the loading course is also the trajectory of the COP in the support phase. While on the right foot the trajectory of this point can be indicted as “conventional”, there is a quick shift of loading from the heel to the front part of the foot on the left foot (smaller density of points in the central part of the foot). The subject employs this type of movement from take-off used in sports also in common daily locomotion. This is, indeed, an important finding that can be in the future negatively projected to problems in the movement system.

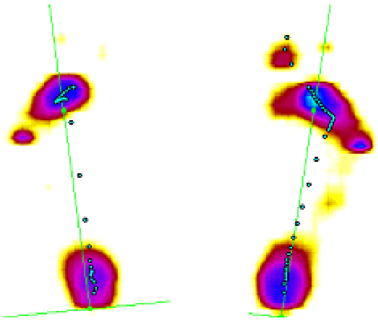


Fig. 8.16. Graphic representation of the distribution of pressure on the foot contact when walking – top sportsman, left limb is the taking-off one.

## 8.2 Summary of selected terms when using videography for the analysis of movement

| | |
|---|---|
| **A/D converter** | Device for the converting of analogue signal to digital |
| **Absolute error** | The difference between actual and measured value |
| **Accuracy of measuring** | Quality assessment of a method by means of the difference between real and measured value |
| **Active markers** | Markers that emit electromagnetic waves (mostly in the infrared parts of spectrum) |
| **Analogue record** | Signal that is created by analogue quantity (voltage, electric current etc.) |
| **Analytical method** | Method for the determination of the human body center of mass; it uses the marking of certain points on the movement record |
| **Automatic tracking of coordinates** | Record evaluation without direct involvement of the evaluator |
| **Calibration frames** | Device for calibration on which there are points with strictly defined distances (coordinates) in a space |
| **Camera calibration** | Determination of the influence of camera parameters on the difference in real and image coordinates |
| **CCD (Charge Coupled Device)** | Optoelectronic transformer for the transformation of the optical signal to electric |
| **Digital record** | A type of a record when the analogue signal quantizes in time and changes into a digital coded discrete signal |
| **Digital signal filtration** | Elimination of bias components from the signal by means of their filtering-off |
| **DLT (Direct Linear Transformation)** | Mathematical method for the transformation of coordinates from plane to spatial |
| **Field** | One half (comprising either of odd or even lines) of a frame |
| **Frame** | Image made by full number of lines |
| **Genlock mode** | System of impulses for time synchronization of records from scanning cameras |
| **Global system of coordinates** | System defining space where the movement takes place |
| **Horizontal resolution** | Number of units (points, pixels) on the line of the evaluated frame |
| **Human body center of mass** | Points of application of a gravity force that effects the human body |
| **LED (Light Emitting Diode)** | Luminescent diode serving for the designation of points on the human body |

| | |
|---|---|
| **Local system of coordinates** | System that is related to a part (segment) of the monitored object |
| **Manual tracking of coordinates** | Determination of point coordinates through its designation by the evaluator on the record of the locomotive activity |
| **Measuring error** | Difference of a value obtained in the measuring process from a real value |
| **Panning** | Camera rotation on a horizontal level in the movement record |
| **Passive markers** | Markers from common materials, or markers covered by reflexive material that enables light reflection |
| **Perspective error** | Distortion that results from a segment moving beyond the plane that is perpendicular to the camera axis |
| **Pixel** | The smallest area given by the number of lines and columns, that forms the resulting frame (image) |
| **Polynomial regression** | Use of polynomials for the elimination of errors (smoothing) from raw data |
| **Precision of measuring** | Comparison of the difference between values obtained during multiple measuring of a given parameter |
| **Qualitative analysis** | Analysis of a monitored activity without the determination of the size (quantification) of output quantities |
| **Quantitative analysis** | Analysis of a monitored activity with the determination of numerical values of elementary (physical) quantities |
| **Raw data** | Values obtained in the process of video record evaluation without further modification of this data |
| **Record digitization** | A process of the video record evaluation by means of designation of selected points on the record of a locomotive activity transformed to PC |
| **Relative error** | The extent of the absolute error expressed in the percentage of a real (measured) value |
| **Relative segment weight** | Percentage value of the segment weight referring to the total body weight |
| **Resolution** | The smallest step that we can measure or distinguish in the process of measuring an object of measuring or on the measuring instrument |
| **Smoothing** | Elimination of certain components from signal that serves to decrease or eliminate errors in “raw” data |
| **Space calibration** | Determination of coordinates of known points in a space for the derivation of relation between real and image system of coordinates |

| | |
|---|---|
| **Spline** | Spline is a special function defined piecewise (definition is given differently on disjoint subsets of its domain) by polynomials |
| **Stick figure** | Sequence of real shots or schematic representations that serves towards the graphic representation of a piece of locomotive activity |
| **Synchronization of cameras (records)** | Camera records setting in order that the corresponding frames from different cameras catch the monitored object at the same moment |
| **Tilting** | Camera rotation on a vertical level during the movement record |
| **Time resolution (frequency)** | Number of frames recorded in a given time unit |
| **Transformation of coordinates** | Transfer of plane (2D) point coordinates on spatial (3D) coordinates |
| **Vertical resolution** | Number of lines in the evaluated frame |
| **Videography** | Procedure for the movement analysis by means of the video record assessment |

## 8.3 Forensic identification persons by traces of human locomotion and its digital consequences

Forensic clues with functional and dynamic features and habits are based on large automatisms, and hence are dynamically stable. Their principle lies in established dynamic stereotypes. However, these stereotypes are not absolute and presuppose certain variability limits, which are necessary for the adjustment to common, non-substantially changing conditions. When the conditions change dramatically and take the character of domineering factors, the performance of habitual activities is disturbed. Variability in the performance of habits is influenced by various groups of domineering factors; it has a selective character, i.e., the changes are clearly determined or statistically dependant on their causes. Therefore this type of selective variability contains information on the conditions in which the habit has been performed (Rak, Porada 2008, pp. 215-230).

Functional and dynamic habits of locomotion are relatively stereotypic. On the other hand, they are variable within certain types of movement such as rapid or slow gait, running, and so on. The gait of a walking individual can undergo significant changes under the influence of external factors, such as carrying heavy weights, uneven paths (steep decline or climbing) and internal causes (pain, tiredness stress and so on). Forensic clues reflecting functional and dynamic features and movement habits have been described elsewhere (Straus 2001, Porada a kol. 2001, Straus, Porada 2006). The principle of these clues is based on a material reflection of the dynamic stereotype and may be defined by the feature of the musculoskeletal system according to a new classification (Straus, Porada 2009).

### 8.3.1 Biomechanical analysis of human locomotion

Experience and logical reasons allow us to make the statement that an individual creating a track makes material changes to the object receiving the track that represent a certain reflection of some somatic properties and of the movement pattern of the individual creating the track. One can say that a track created by a human has more or less its large biomechanical content (Karas, Porada 1977). When analyzing the track, it us unavoidable to use an approach enabling the examination of the sum of all traits and their specific relations. For this reason it is also necessary to perform a general consideration of the complex set of locomotion tracks and to create a general system and a matrix of traits in this complex set. Generally, the following traits can be classified: geometrical, kinematic and dynamic. Geometrical traits and especially newly defined kinematic traits (traits reflecting the manifestations of the locomotion stereotypes) are critical (and should be performed) for the forensic identification of individuals according to their locomotion pattern.

The comprehensiveness of a biomechanical content of a trace is determined by the number of traits (minutiae) that can be found in the trace and that can provide information on individual characteristics of the movement and behavior of an unknown individual. These specific traits or sets thereof, trajectories, which are essential for individual identification, must be properly fixed and documented. During the procedure, it is necessary to examine the sum of all essential traits and to investigate their specific relations (Porada 1981).

### 8.3.2 Tasks and possibilities of the analysis of locomotion traces in terms of geometry and kinematics

Traces of human locomotion are studied in various manners and with various objectives. Most works, in which traces of human locomotion were analyzed in geometrical and kinematic terms, are characterized by a descriptive approach, usually with a narrow focus on any of the special questions, and provide no additional or required connections. Suitable technical resources and demonstrable statistical evaluation of measured or detected data are absent, which means it is not possible to make valid conclusions for identification purposes.

Forensic identification is based on theoretical analysis and related principles of identity, individuality and relative stability of the objects of identification. The theory of forensic identification perceives identity as a relationship between two or more manifestations (conditions) of the same object present in various forms, wherein these manifestations (conditions, transformations) may be considered to be an expression of an identity relationship only within a certain compact system. The introduction of any new identification method in criminology must respect these principles and fully comply with the essential conditions, even for searching the possibilities of individual identification of persons or determination of a group membership according to a movement manifestation of bipedal locomotion.

Based on the analysis of theoretical considerations on identical features of the dynamic stereotype of human locomotion and dynamic stereotype of the writing process, as well as long-term results from the investigation of these dynamic stereotypes, and evaluation of large-scale experiments and research, especially from the study of handwriting, we have well-founded reasons to believe that the principles of modified Quetelet's theory of unchangeability and relative stability of the dimensions of human bones after reaching a certain age can be applied, by means of derivation, on the dynamic stereotype of human locomotion, based on theoretical considerations and their sequences. This constitutes an objective nature for the individual identification of persons according to functional and dynamic traits in terms of classification of traits according to characteristic qualities (identical, different and contradictory traits):

1. The extent of individual differences in the locomotion of any person is lower than the difference between this and any other manifestation of locomotion.
2. The extent of conformities in the locomotion of any person is higher than the conformity between this and any other manifestation of locomotion.

A target-oriented research of these principles (or confirmation or falsification thereof) should also focus on the following important aspects:

a) Special features in the investigation of patterns of dynamic stereotypes should never be evaluated from only a single point of view;

b) Mutual relationships between the special features in the patterns of dynamic stereotypes of locomotion and their extent, work character or motivation are essential for the proper formulation of requirements for comparator materials;

c) Appropriately evaluated special features of investigation constitute, in their consequences, a condition for proper interpretation of the traits for technical and tactical use within forensic identification.

These principles must be applied objectively and fully. However, their strength and effectiveness is dependent to a certain extent on the method of investigation and experiences of the researcher. In the experts' practice, when determining identification traits (minutiae) of the pattern of dynamic stereotype of human locomotion, it is necessary to apply all standpoints which should be used as a basis for classification of traits, so that these traits provide an overall picture of the investigated patterns of locomotion, capable of managing the issue of personal identity according to dynamic stereotype (modified according to Blažek, Valeška, Porada (1984).

### 8.3.3 Gait-based recognition of individual identity

Gate-based identification of a human is one of the newly emerging areas of biometric applications. The advantage of the gate-based identification is a contact-free design of this technique compared to the majority of other biometric methods. This method is not intrusive at all (as compared to fingerprints, palm prints, hand geometry, iris- or retina-based identification, and so on), and causes no discomfort in the humans.

Gait is closely related to other areas of human knowledge, such as medicine, psychology, tracking and modeling of human body movements, including emotive stimuli. From this point of view, it is apparent that gait is acceptable even as a subject matter of biometric investigation and subsequently for the development of functional applications based on biometric principles. Methods of "computer seeing" are used in practice to obtain required movement characteristics for biometric recognition.

Early results of research obtained ten years ago confirmed that gait has a large potential for identification and verification tasks. Only further extensive research in the area of new methods using computational technologies will confirm whether gait will be an equally effective and sufficiently powerful biometric alternative to other biometric methods that are already frequently used in practice, so that gait-based analysis in humans becomes an additional pragmatic options for the selection of application resources for the management of various safety tasks.

Gait biometry is associated with high hopes, especially in relation to physical safety and potential use of the already introduced technical resources for safety purposes. A possibility exists to use already installed industrial cameras, monitoring systems upgraded for the automatic evaluation of human identity (even retrospectively) based on the methods of facial and gait recognition (independently or together). This interest is strongly supported by a growing incidence of terror threats and other violent crimes that require real-time or at least subsequent situation analysis.

Many biometric applications cannot be introduced or effectively used under certain conditions. For example the face of a person may be hidden (typical masking during the assaults of financial institutions), or poor light conditions (dark, underground premises, and so on) or poor resolution make further processing of the obtained image impossible. The human ear may similarly be invisible for a simpler reason, such as being covered up by hair or intentional masking.

Gait has many specific individual features that on the one hand facilitate the use of gait for identification purposes but on the other hand impair technical automated identification or verification. A delinquent robbing for example a financial institution may intentionally move very slowly to avoid any suspicion compared to the behavior of other persons, or on the contrary, he may run fast to reduce the time of staying within the reach of camera monitoring systems. A slow gait or a fast run are a natural manner of movement for almost anybody. This may provide quite different conditions for the use, selection or combination of technical resources with various methods of “computer seeing” and for the subsequent practical evaluation of the situation.

In other words, there are limitations for use of gait in biometric applications or very specific technical means should be used for various types of tasks related to the gait-based identification of humans.

There are many other factors that influence the movements and gait of humans. Various types of apparel change not only the manner of gait but also the external appearance of human individuals, and overall behavior. Contemporary literature in the area of computational seeing, recognition of textures and figures contains many contributions that focus not only on the evaluation of gait but also on the evaluation of human silhouette and other factors. Pregnant women also change their gait and external appearance, and any object carried by anybody has an influence on the resulting pattern of movement. Various diseases or fatigue-related disorders of the feet or legs or any other diseases influencing the posture and movement of the body, whether short-term or long-term, have similar manifestations, including common drunkenness or conditions under the influence of an addictive or hallucinogenic substances, fatigue, injury, and so on. Gait can also be changed quite purposefully. The resulting pattern of gait is influenced by many factors, such as speed/acceleration of gait, length of steps, body dimensions, movements of arms, material of the walking surface, and others. In addition, technical and physical conditions of imaging also influence the final gait pattern – various angles from which the cameras capture the scenery, influence the resulting perception of movement, which is different under standard conditions, and provides completely different identification characteristics of gait. We must also consider light conditions, for example shadows may substantially influence the extraction of human silhouette from the background. The color of clothing, if it blends with the surroundings and so on, has similar effects.

But the said factors are not unknown for biometric applications, and many biometric applications count on them and can eliminate or effectively evaluate them using evaluation mechanisms. For example, facial recognition in the first applications was dependent on glasses, facial mimics, haircut, and other factors. All these factors in the new applications have no effect on the result of identification of the person against a reference sample. On the other hand, we should realize that gait-based recognition of humans is a very specific task in very complicated operative conditions.

When using facial recognition of humans, the reference images are taken almost in laboratory (standardized) conditions, such as in offices that keep state administration/civil files and related tasks. For this reason, photographs for the need of digital passports are no longer taken in common photo shops that were not able to guarantee the standardized quality. Also, the evaluation of faces for example at airports is much easier that in an open terrain since a uniform single color background, optimal light, and minimum movement of other people can be ensured in certain dedicated rooms.

On the contrary, gait-based biometric identification is supposed to be used in common terrain and environments (such as streets, squares, public or closed premises, various corridors and passageways, transfer transport knots, garages, financial institutions, and others) that are monitored by industrial cameras and the images are directed at operation centrals. This environment has not been standardized in any manner to date, in terms of applications for gait-based identification of humans; different numbers of cameras, the scenes are captured from various angles and distances, or in very poor light conditions. From all this information it is evident that gait biometry is today among the most complicated areas, and few results have been thoroughly confirmed in practice. This is also due to the fact that gait biometry is one of the youngest disciplines, in which neither researchers nor technicians have been thoroughly interested until recently. Nonetheless, this fact does not mean that the tasks of gait biometry are not manageable.

### 8.3.4 History and medical research

The essentials for experimental recognition of gait were established by Johansson (1973) in an experiment with point-light display (PLD). His experiment confirmed the possibility of identifying type of movement by observing two-dimensional movement characteristics of light sources attached to human body. When the light points were observed in the static mode, they resembled the stars on a Christmas tree.

Once they started to move, they represented the movement of the examined person. It was shown later that point lights can be used to identify various types of movements. Jumping or dancing was easily recognizable, as were also more sophisticated movements characterizing type of gait or event human identity. These findings in 2001 led to a conclusion that human gait dynamics is unique to each person and can be used for biometric purposes (Abdelkader 2001, Nixon, Carter, Nash, Huang, Cunado and Stevenage 2001), and thereby for the management of identification tasks (note of authors).

The objective of medical research in the field of gait was and still is to identify respective elements of gait in order to treat pathologically abnormal persons. Murray (1967) described standard movement characteristics of pathologically normal persons that were compared to the gait characteristics of pathologically abnormal persons. The data collection system uses required defined minutiae in relation to the study subject. This approach is typical for most data collection systems for medical purposes, but is not suitable for identification tasks. Murray considers gait as a picture of overall gait cycle, in other words, the gait can be understand as a periodical signal.

The gait cycle is defined as a time interval between two corresponding time points, when the heel of the same leg touches solid ground in consecutive steps. Each leg moves in two mutually separated time periods – in the stance phase (the foot touches the ground) and in the swing phase (the foot is not in the contact with the ground and swings ahead for the next step). The cycle starts when the heel touches the ground for the first time and this time point means the beginning of the stance. After the contact of the heel with the ground, the entire foot touches the ground and at this moment, the entire weight of the body is moved thereon. Meanwhile, the other leg is in the air and swings ahead to touch the ground again. The author defines separately the lengths of steps from the right to left legs and vice versa, and length of step of the right (left) foot and the overall time of the gait cycle for the right leg. A step is a movement between corresponding contacts of the heels with the ground; the complete gait cycle comprises two steps (Fig 8.17).

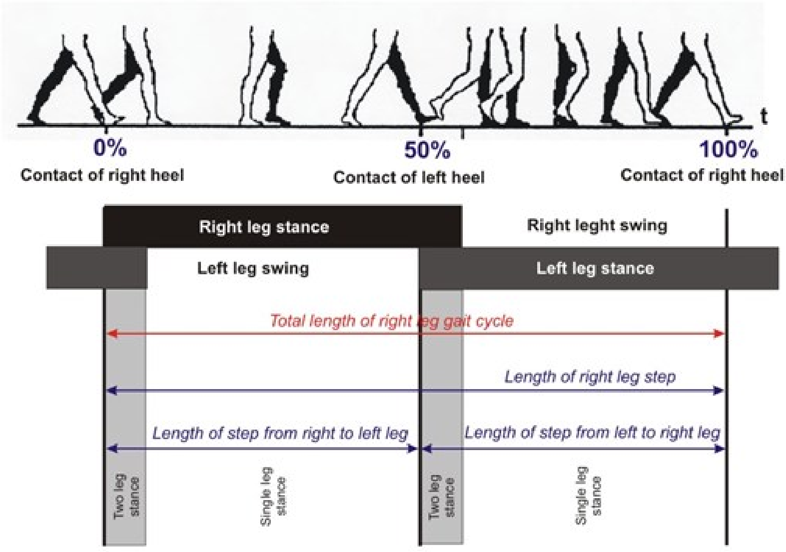


Fig. 8.17. Time relationship between the individual components (phases) of gait cycle according to Murray. The entire gait cycle is closed after two steps (100%). This time cycle of gait to the extent of 0–100% of the axis is often used in further considerations and graphs.

The stance phase forms 60% to 62% of the overall gate cycle, while the swing phase 40% to 38% in normal gait tempo. The faster we walk, the higher the proportion of the swing phase. When walking at normal gait tempo, an average adult individual makes 113 steps per minute with an average step length 70.1 cm.

Murray (1964, 1967) proposes that if we take into account and measure all components of gait, then we could consider gait to be unique for every individual. His work, however, deals with twenty different components of gait, some of which are measurable only from the view of the vertical body axis, i.e., from above. Murray also discovered the fact (Muray 1967) that rotation of the pelvis and chest is highly variable n different study subjects.

The required components for the identification of gait are, unfortunately, very complex, and it is almost impossible to obtain them as an extract from real-time images (captured by a common industrial camera) of the moving object. Even if we measured all components of gait, it would be so complex that it is virtually impossible to create the required application for automated identification purposes based on this approach.

### 8.3.5 Recognition of gait from the movement (trajectory) of the center of gravity

Bipedal gait (on two legs) substantially differentiate humans from other beings and results from many years of evolution. This gait mode enabled humans to walk upright, to raise the head, to move in a complicated terrain and mainly to liberate hands for other activities. The physical consequences resulting from the anatomical construction of our body is that a human cannot maintain his/her center of gravity in a direct line (such as for example the wheel), when moving, which is not optimal in mechanical terms.

The movement of the center of gravity of the human body has the character of an undulating curve. This fact is of critical importance for the identification of our walking pattern. In medical terms we can decide whether this pattern results from the movement of a healthy body or not, while in recognition terms, we can discuss the recognition of group or individual identity.

The movement of the center of gravity, or monitoring and subsequent evaluation of its trajectory, historically belonged to the first directions of medical, biomechanical, and identification/verification research. Figure 8.18 shows schematically the first very simplified theoretical approach to the monitoring of the center of gravity of the human body.

Modeling was used to add other aspects to this movement, such as bending (movement) in the joints, such as hips, knees, or ankles, rotation of pelvis and chest, and the flexibility of human body was taken into account, such that the final curve was “refined” until it achieved a sinusoid course.

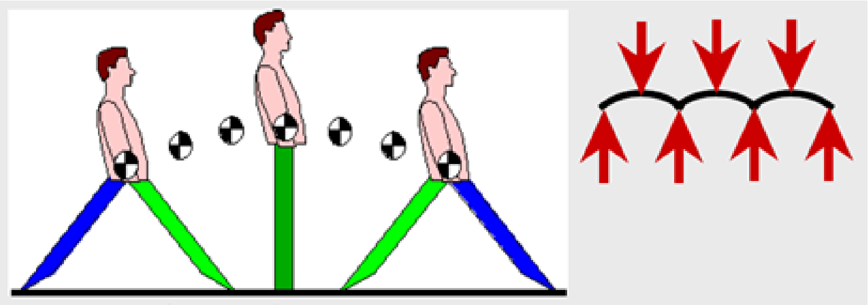


Fig. 8.18. A very simplified view of the movement of the center of gravity of the human body. The legs are straight without any bending in the knees or other joints, non-flexible. The trajectory of the curve is shown on the right, arrows represent maximum and minimum values (Patton 2001).

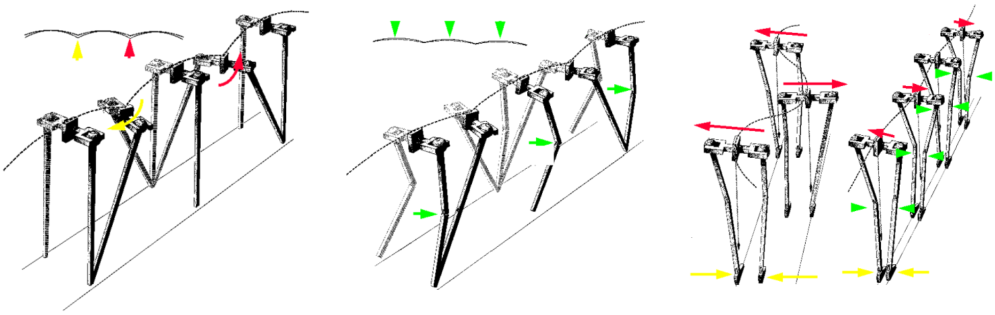


Fig. 8.19. Example of the gradual modeling of the gait movement. The picture on the left shows a very simple module comprising only single leg support; the middle picture shows a simple movement in the knees, while the picture on the right shows the addition of pelvis rotation and distance between the feet (Patton 2001).

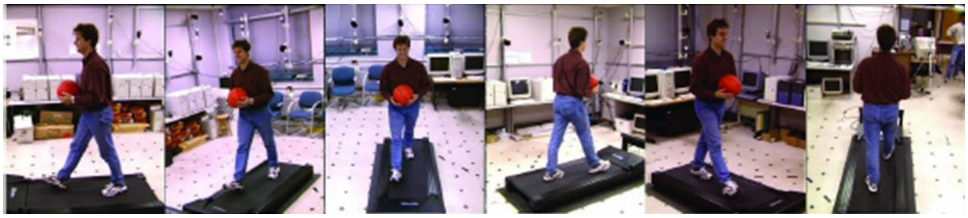


Fig. 8.20. An example of a very simple experimental measuring of gait parameters in the approximate center of gravity (carried ball) at different speeds on the running belt. Experimental database of CMU[1], containing six simultaneous video-sequences of 25 persons captured from different angles (Gross, Shi 2003).

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[1] CMU - Carnegie Mellon University.

Historical observations and deep research, mainly in medical and biomechanical disciplines, based on the evaluation of the center of gravity trajectory, revealed that each leg is loaded by approximately 55% of human weight alternately during walking, and the center of gravity during the gait moves up and down and from side to side in sinusoid waves with an amplitude of around 5 to 6 cm.

Since the center of gravity of the human body is not directly visible, many authors monitored movements of the scalp, middle of the ear [25], and so on, during identification tasks. The course of movement of the center of gravity of the human body and the middle of the head (ear) projected into the graph of the gait cycle is similar but not identical. The movement of the head shows higher amplitudes compared to the center of gravity of the body.

### 8.3.6 Sagital kinematics

The angle is measured throughout one gait cycle (during which contraction and release of muscles occur to allow movement) and is shown in graphs similar to the examples on Figure 5. In this manner, several parameters of gait can be measured in any individual during the gait. This method was primarily intended purely for medical purposes, but with time, it found its use in biometric evaluation of human gait, in particular in the area of computational seeing, which employs the method for measuring “essential characteristics” in this specific case.

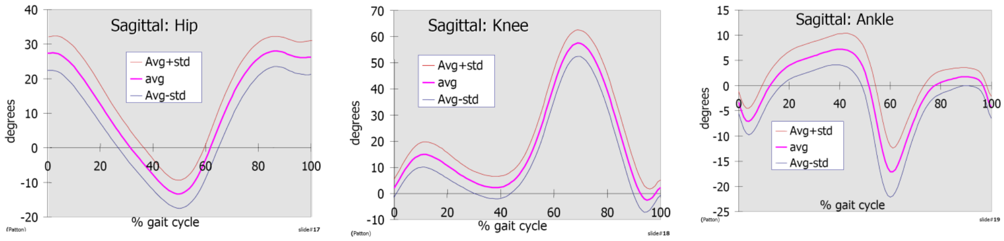

Fig. 8.21. Examples of measuring sagital angles of hips, knees and ankles. The middle curve in each of the three graphs represents an average value, while the upper and lower curves represent maximum and minimum standard deviations (Patton 2001).

The set of courses of partial sagital characteristics summed together defines the overall gait characteristics of a given person.

### 8.3.7 Principles of automated technologies for the recognition of persons according to their gait in a digital setting

Recognition of persons according to their gait is one of the youngest disciplines of biometry, the development of which was conditional on having sufficient capacity of computer memory and processing speed of a huge quantity of image data sequences. The first big project was DARPA[2] focused on distant identification of persons (Sarkar, Philips, Vega, Grother, Bowyer 2005), which collected a large amount of data and worked

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[2] Defense Advance Research Projects Agency. <http://www.darpa.mil/>

out the first computer algorithms for automated recognition of human gait. Since the beginning of the DARPA project, data collection and working on other new and progressive methods and technologies has continued. Knowledge, methods and manners of application from other biometric fields are commonly used in gait-based recognition of humans.

Biometric gait-based recognition of identity is currently oriented in two basic directions, according to the analytical methods used. We differentiate among approaches based on silhouette processing of a moving object (humans) and approaches using the modeling (recognition) of movement.

### 1. Model oriented approaches

Model-oriented methods are based on the analysis of movement of the trunk (upper part of the body) and/or legs. Unlike the method employing the silhouette of a moving object, the efforts of this method are focused on the dynamics of the movement rather than on its shape (silhouette). Attention is being focused on different body dimensions (lengths) and angles during the gait, as shown in medical approaches. This approach disregards some aspects, such as the influence of clothing on a person's gait.

Historically, the following three basic models appeared in the model-oriented approaches: wire, cylindrical, and oval (drop-like) – see Figure 7.22; other models were used in exceptional cases. Model-oriented approach was historically used for extraction and further monitoring of movement, including but not limited to identification purposes. Effectiveness of recognition depends on the selection of the appropriate model. The wire model was and still is being used for its simplicity and possibility of use in 3D-modeling. Individual components of the wire model begin and end in the joints. Different authors use various number of model components. The lowest number is 6 components: 2 for the arms, 2 for the legs, and one for the trunk and head. In one model (Lee, Chen 1985), authors used 14 connection points (joints) and 17 segments, while volumetric modules describe and subsequently use even 25 connection points and 24 segments (Little, Boyd 1995). Older literature contains a large quantity of models as defined by the respective authors who further developed their theories on the basis thereof. The model-oriented approach is sometimes called parametric approach. It is invariant in terms of view but requires a calibrated camera system.

### 2. Approaches oriented to the evaluation of the silhouette of a moving human

Approaches oriented to the evaluation of a silhouette extract the silhouette of a moving object from the background of the scene (i.e., a human in the case of person identification according to gait). They track and analyze the silhouette (for example by various averaging) and/or its movement. Even here we can find a myriad of various methods and algorithms, which are summarized in (Nixon, Carter 2006), including a list of other contemporary scientific literature on this topic.

Silhouette contour length analysis is one of the methods used in contemporary practice. It is transformed into a graph and normalized before further processing. The idea is apparent from the following figures (Fig. 8.22, Fig. 8.23). Figure 8.23 shows contour lengths of different persons.

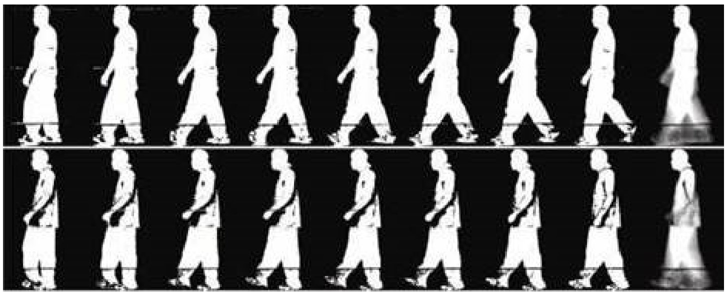

Fig. 8.22. Phase movements of a silhouette of an individual walking, captured by a camera after computer processing (htpp://www.vislab.ucr.edu/research/clip01)

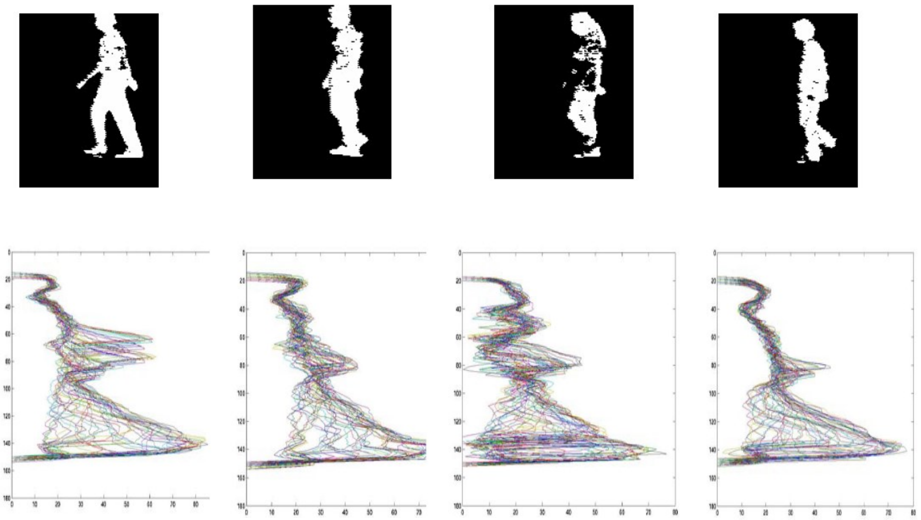

Fig. 8.23. Contour lengths of four different individuals (http://www.umiacs.umd.edu/2006/tutorial gait.pdf).

## 3. Database of gait records

Reference databases containing video records of gait are established at many civil and military institutions so that the research of new methods for gait-based recognition of persons is effective. The databases contain records on dozens or hundreds of different persons in various conditions. The records are captured in a manner allowing certain standardization for use in laboratory or real conditions. If we have for example one reference database of records that complies with the requirements for several research subjects together, such databases can be used to compare the efficacy and performance of various algorithms applied in a specific SW product.

Some databases are limited to a certain group of contributors, others are publicly accessible. Given that biometric research and processing of gait is still new, database funds are not that high compared to those for fingerprint or face databases. But the data files are extended continually and help create suitable conditions for the comparison of results between the respective individual biometric applications/methods, as proposed by different research groups, thus providing a certain independent objectivity with respect to data obtained by somebody else.

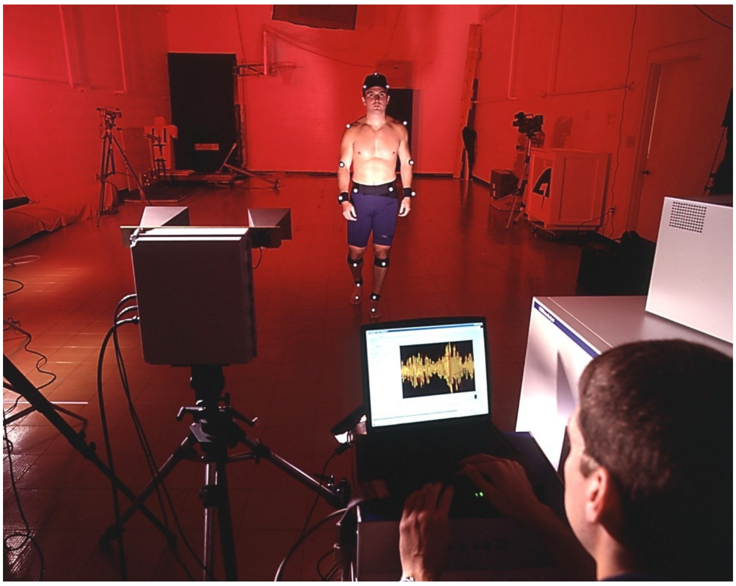

Fig. 8.24. Records of movement– gait are captured in world research centers under standardized conditions using one or more simultaneous recording cameras, and then stored in a database for subsequent use (http://www.gtresearchnews.gatech.redu/gait 1.jpg).

The database of UMD (Universities of Maryland) is among renowned data files containing data obtained on the terrain, simulation and tracking scenery data or databases of Carnegie Mellon University's (CMU) known as Mobo with parallel records of persons on the running belt in interior settings. The other database NIST (National Institute of

Standards) and University of South Florida contains 1,870 sequences from 122 persons, wherein the movement of each person was captured simultaneously by two cameras. The interesting part is that records were taken for various types of shoes and for grounds with different characteristics.

A unique advantage of gait-based human recognition is its long-distance applicability, where other biometric methods cannot be used at all due to their nature or principle or the obtained images (such as facial image) have a very low resolution. Gait is recognized from image sequences using common or brand new technologies of computer vision. Currently the technologies are sufficiently effective and have a potential comparable to other biometric methods. In a similar manner, the area of gate-based human recognition undergoes development in terms of reference databases. The quality and quantity of records have been increasing continually and follows the trends for biometric facial or voice recognition.

Current knowledge and results of applications clearly indicate that a human can be recognized by his/her gait pattern.

A completely open question is how much the gait-based biometric identity of a human individual is acceptable for forensic purposes, if used as evidence adduced in a trial. What is the resolution of biometric methods working with gait phenomenon? The individual researchers, research teams or specialized firms in commonly available materials talk about ninety percent reliability, i.e., 90 persons of 100 (current experiments are usually carried out with a similar order of resolution) are properly identified. This does not mean in any manner that every human individual from the sample of for example one million people has his/her unique gait pattern, which is absolutely different from that of the others, similarly to analogical fingerprints or iris prints, where the identification precision is much higher (1:$10^9$ and more).

Automated analysis of human gait is a subject of interest of safety teams even for purposes other than mere identification. It is an automated tracking of a person (or several persons) in a certain area covered by monitoring cameras (such as municipal circuits, closed circuits in specific buildings (with a high level of safety) – large buildings, and in theoretical cases, even from space satellites). As the person walks, he/she moves from the visual field of one camera to another. Automatic gate recognition system is able to transfer the person from one camera to another and switch captures from different cameras automatically tracking the person or group of interest, to an operational officer on duty in the operation center on a single monitor.

## 8.4 Forensic biometric identification

First of all we have to explain the notion of *general identity* and *identity of person*, which terms are in close relation with term *identification of person*. Identity of a person (people`s identity) is extremely delicate philosophical, psychological andsocial category.

**Identity** (lat. *identitas*, from the word *idem* = equal) is used when compared notions, objects etc. can be interchanged in such a way that we can put the sign of identity between them. So we understand the identity as equality of something with something else or with itself (Rak, Porada, Mesároš 2008, pp. 183–214).

## 8.4.1 General identity, identity and identification of presons

- The principle of identity is the basic term in classical logic: every object is identical with itself.
- Identity of a person is defined as „inevitable condition of existence of every concrete person“, or as „the condition to be himself and nobody else“. People`s identity is a kombination of biological, physical, inborn or obtained individual and specific features and abilities to perceive himself.

We have several points of view on identity of a person:

- Biological identity is combination of inborn and obtained biological features of a man, which are independent on the human concsciousness.
- Identity of a person in the point of view of psychology means the identity of a concsciousness.
- Identity of a person is so often connected with terms as „personatily, individuality and individualisms“.
- Identity of a person from the point of view of philosophy means to identify the human being with human thinking.
- Social identity: a person according his own features, demonstrations and habits belongs to a social group of persons having identical features.
- Every person in its course of life can receive several varied identities, some of them are using varied identities at the same time. It is not necessarily to be connected with the persons with criminal or intelligence activities. Actors, artists etc. belong into the group too.
- Receiving of a multiplicate identities can be legal or illegal (Rak, Matyáš, Říha a kol. 2008).

## 8.4.2 Identification of a person

Identification of a person is an extraordinary and particular case of a general identification. Above mentioned reality leads to the conclusion that we can think of external identification and internal identification (self-identification). Under the term *external identification of a person* we understand the establishing of physical (biological) identity of a human beeing, under the term *internal identification of a person* (*self-identification*) we can find the perception of psychological, philosophical and social self – identity.

### 1. The basic view on the identification of a person

We can look on the identification of a person from many different points of view, we can utilize several different methods and algorithms too. We distinguish persons according his physical look, social behavior, according his role of interaction with his environment, what is his name, his name in his society (name, surname, nick name) in his family and in his work (where he works and is holding some positioin) and among his friends. We can identify a person according his properties, knowledge and occupation. It is possible to identify a person according his physical, biological and genetical features (Rak, Porada 2003).

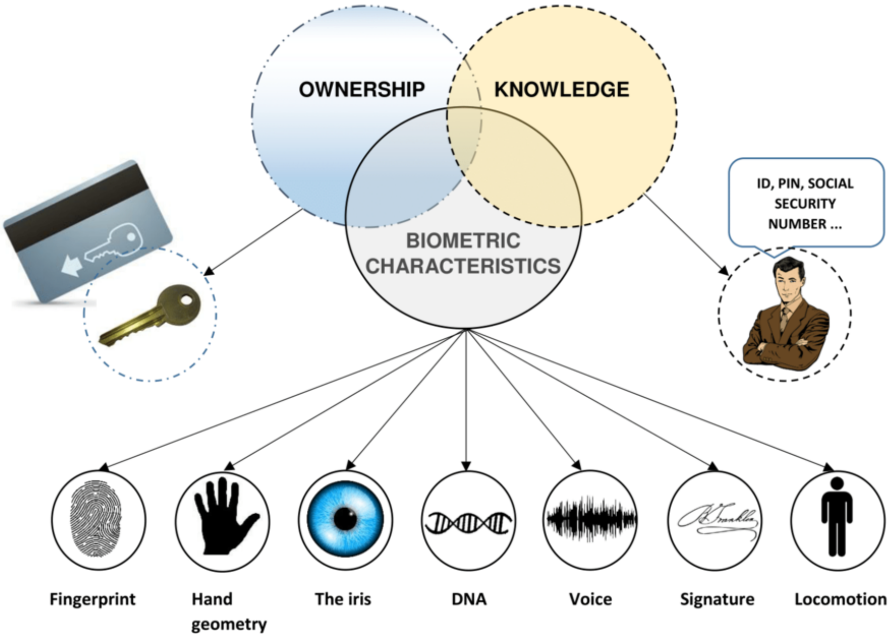

Fig. 8.25. Basic methodes of identification of a person (Rak, Matyáš, Říha a kol. 2008, modified).

Basic identification of a person can be done by following three methodes (Rak, Porada 2006):

- **property** of some external, given features of the properties of the individual person,
- **knowledges** of a concrete person,
- **biometrical features** of human body anf its demonstrations.

## 2. The basic idea of biometrical identification

According to the basic principle of identity *every person is identical only with himself.* If we can scientifically prove (and i tis already prooved) that also our physical (as well as psychical) features are unique, then they can be successfully used for effective identification of a person wit the very high degree of originality.

The basic idea of exploitation the features of human body and its behavior for identification purposes is coming for centuries. Identification based on fingerprints (dactyloscopics) was known by the ancient Chinese. Citizens of Babylon used the finger print in the process of ratification of business agreements as a signature on the clay tables. Numbers of scientists and researches, often educated in medicine, was occupied by the introduction of dactyloscopy into the criminology practice. For example, *Sir William J. Herschel* has used fingerprints in India as a proof in receiving the finance means since 1856.

French scientist, etnologic, *Alphonse Bertillon* introduced for identification of persons into criminalistic practice in France the method based on description and geometrical measures of dimensions of human body and head and on the base of them he divided peoples into 243 categories.

Comercial utilization of the biometrical identification started in the year 1970 by the system nemed **Identimat**, which measured the geometry of palm and which was used for entrance into investment group *Shearson Hamill* on the New York Wall Street (Rak, Matyáš, Říha a kol. 2008). Technology AFIS step by step penetrates into civil sector too, where, in industrially developed countries, became the basement for checking the entrance (into buildings, technological or computer sites, bankomats etc).

The very first method for identicifacion of person on the base of his retina was introduced into practice in the year 1980. The work of mathematician *Dr. Johan Daughman* from Cambridge University has made the fundament for industrially utilized identification of persons by their iris.

Identification of person by computerized features of human face or signature is even more new. At the end of 20. and beginning of 21. century is intensively processed human gene and the technology of identification of person by DNA is to be equally revolutionary.

The other methods allow us to identify a person according his voice. Investigation is going on even focused on identification of a person according the smell of human body. Even this technology brings no surprise into the case, as it is used effectively a long time ago by trained dogs.

### 8.4.3 The place of biometrical identification in todays world

To the advantages of biometrical identification belong:

- it is not possible to forget or loose it,
- it is very difficult (even not posssible) to be stolen or falsify,
- high velocity and accuracy of identification,
- it is very easy and quickly prepared for usage,
- it is natural for man,
- it is very easily managed today,
- possibility of full or partial automation.

### 8.4.4 Biometrical identification and verification

*Basic definitions and terms, division of biometrical identification and verification*

Biometrical identification is the usage of unique, measurable physical or physiologic features (so called markants) or people`s demonstrations (men behavior is to be understand as lot of his demonstrations) for the unambiguous detection or checking of his identity (Rak, Matyáš, Říha a kol. 2008).

Under the term *biometrics* we can image measurable features of living organisms which are scanned, processed and evaluated and saved in the process of identification or verification.

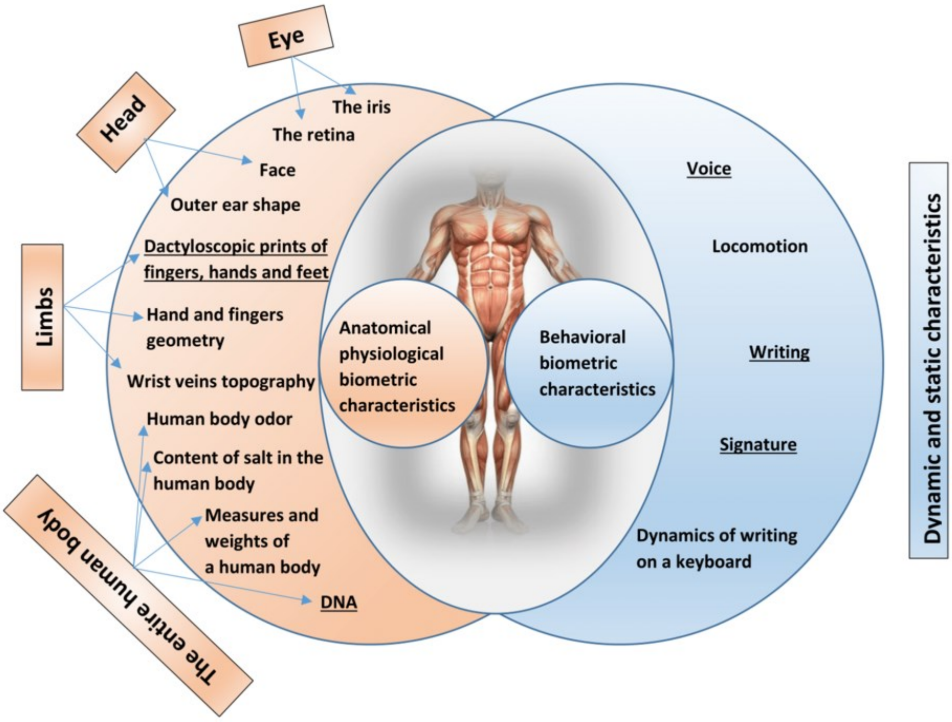

Fig. 8.26. Two basic access to classification of biometric identification, with the presentation of identification methods. Present are new methods, whose are investigated intensively in scientific and research laboratories. Methods, generally used in police and court praxis are underlined in the picture (Modified by Porada, Rak, Mesároš 2008).

For identification of person there are used specific features of the human behaviour, which are called *behavioral* in specialized literature.

Assumption for the usage of every feature is its originality, stability, practice measurability and technical possibility of following processing aimed to evaluation the comparable features belonging to different individuals.

Biometric identification is automatic utilization of individual, measurable anatomic or physiologic features or demonstrations of man for unique finding out or checking his identity.

**Anatomic–physiologic biometric features** are used for identification or verification of peoples on the base of scientific knowledge of iris, retina, face, shape of outer ear, fingerprints, palm and sole, geomteric of fingers, topography of wrest venus, smell of himan body, content of salt in human body, dimensions and weight of human body, DNA structure etc. Anatomic – physiologic features are unique and stabil.

**Behavioral biometric identification** is based on serious knowledge of the human voice, movement of human body (its individual parts) so called *locomotion* of the knowledge and ability to write.

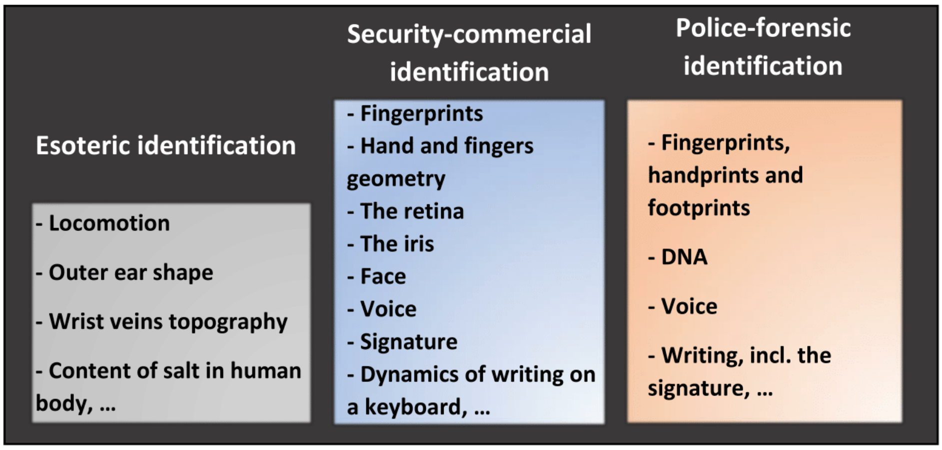

Fig. 8.27. Overall look on possibilities of identification or verification of preron, by whose the access to individual objects is evaluated (Porada, Rak, Mesároš 2008).

The basic schematic separation of identification / verification is on Fig. 8.27.

**Police – court biometric identification, secure – commercial and esoteric**

Biometric identification and/or verification methods according to the accuracy, responsibility, objectivity and the mode of usage can be divided on:

- police – court,
- secure / commercial,
- esoteric.

## Secure - commercial identification

The word *secure* presents here the general security needs, for whose the identification is used – namely security of computers, banks and protection of sensitive personal data. The word *commercial* means that used biometric technologies are available on the specialized market.

The basic advantage of secure – commercial biometric applications is its automated processing. In the application the verification prevails over the identification. To the user the enter to protected objects is permitted or prohibited (computer networks, servers, work stations, mobile phones, bankomats, bank accounts, physical objects, door opening systems, starting systems of automobiles etc.). Accuracy and sensibility of secure – commercial applications is less than that of police – court ones.

The aim of verification / identification in the secure – commercial applications is slightly different from the classical police – expert and court – expert activity. In the work of organs active in the punishment management it is typical to prove the guilt. In secure – commercial region we deal with *positive identification (verification).* Its goal is to prove authorization of entrance – access – to information, objects etc., with the aim to protect the owner of object or data etc. from their unauthorized usage or theft. The aim of positive identification is to prevent usage of concrete identity by several persons.

In secure – commercial biometrical identification today methods based on knowledge of dactyloscopy iris and retina are anatomic dimensions and features of palm, fingers, shape of faces, voice and writing skill are used (first of all the signature and skill to use keyboard).

Secure – commercial technologies are, thank to its broadly spread usage, cheaper than the police / court application. Several periferial external devices (mainly compatible with the computer systems) thought to be used for biometric scanning (e.g. fingerprints) are of the value of one thousand crowns, what is comparable with higher quality computer mouse, working in infrared region and generally used in the computer environment (Philips 1997, Polemi 1997).

## Esotheric identification

Esotheric identification is the last group of biometric identification methods. Esotheric methods are known only for small group of specialists. From this is the term *esotheric – accessable only for consecrated, secret, cover.* In this group belong methods whose are still not widely spread in praxis and sufficiently proved on big sample of tested causes. In no case they are usable for secure – commercial application, they are methods attracting great attention.

Among the esoteric biometrical identification methods we count locomotion (typical features of human walk), the shape of outer ear, lips prints and pore prints, topography of venus, smell of human body, content of salt in human body etc. Newly a row of works and technical devices devoted to identification using alongside marks on human nails occurred, whose can be used likewise as line codes (Rak, Porada 2002).

### 8.4.5 Brief review of the basic biometric identification methods used in general praxis

**Fingerprints**. It is the symbol of the biometric identification existing for thousand of years and for the same time accepted by courts. Method is based on unique pictures of papilar lines.

**Iris.** Colored circle around the pupil of human eye contents specific unique identification points by whose it is possible establish the personal identity wit great accuracy. There are not identical irises. Scanning is done by standard video technology.

**Retina**. It contents enough of anatomic points whose secure high identification accuracy. Scanning of the biometric sample is done by light beam. White retina of the human eye consumed a part of the light beam while part of it is reflected. By this there is scanned the river bed of veins and blood-vessels of retina, being unique for all the life of a person.

**Hand geometry** is considered as ancestor of fully automated secure – commercial identification of person, realized on the base of anatomic – geometric features of human palm and fingers even in 70-ies of 20-th century. Fundamental is measuring of length and width of individual fingers, hips or bones. This method was used firs for the protection of entrance to stock – exchange information and inside the buildings of nuclear investigation in Los Alamos.

**Voice**. Human voice content such biometric features, whose can be interchanged or forgotten. Human voice has biometric and physiologic characteristics. The sound signal of voice is generally transformed into an unique digital code.

**Face**. Face is peculiar to and specific for every person. Effective computer technologies can differ the faces of different persons the same mode as man. Human face contents identification (antropologic) points, whose are specific and unchanged by time.

**Signature**. It is next biometric feature useful for unambiguous identification of person. Today we process not only the static picture of signature but we evaluate the dynamic features of writing too / pressing, velocity direction of pen and other features.

**DNA**. It has all the chances to become the most accurate and the most reliable identificator of human being. It contents a huge amount of information on the every person. Only a small part of them is good enough for identification of a person (Rak, Matyáš, Říha a kol. 2008).

### 8.4.6 Human locomotion

The identification of the persons according to the dynamic stereotype of human locomotion (Šimšík, Porada et al. 2008, Porada, Šimšík 2011) is a new way of identifying a person according to functional and dynamic characters. Locational activity of humans is realized on the basis of movement patterns that are created in the process of each individual's development. The whole motion is the result of a pattern formulated by neuronal activity, which is referred to as a central motor program. Walking is done on the basis of a genetically-engineered model that is modified to take into account the individual characteristics of each individual during ontological development. This physical activity involves a number of common features in performing different groups of people. At the same time, it is possible to find a number of differences with typical characteristics for the individual. The identification of a person according to the locomotive's dynamic stereotype is possible according to the time course of the evaluated identification points on the body of the dummy, which create individual identification curves. Different or physiological characteristics or manifestations are performed in a human way. Because of this identification, unique, measurable anatomical physical or physiological features or human manifestations are used to identify or verify their identity with the often necessary use of computing (Rak, Matyáš, Říha et al. 2008).

The research explored the possibilities and outlined the basic theoretical advantages and peculiarities of criminalistic identification according to functional and dynamic features.

At the current level of walking studies, techniques used to study kinematic parameters can be divided into 2D and 3D methods. 3D methods use more than two cameras that gain parameters from 3D motion of individual parts of the body. 3D reconstruction of the recording is done after calibration of the system. 2D Walking Methods for Biometric Purposes Gain Explicit Data by Walking:

- Through models of the human body.
- Over the shape of the silhouette.

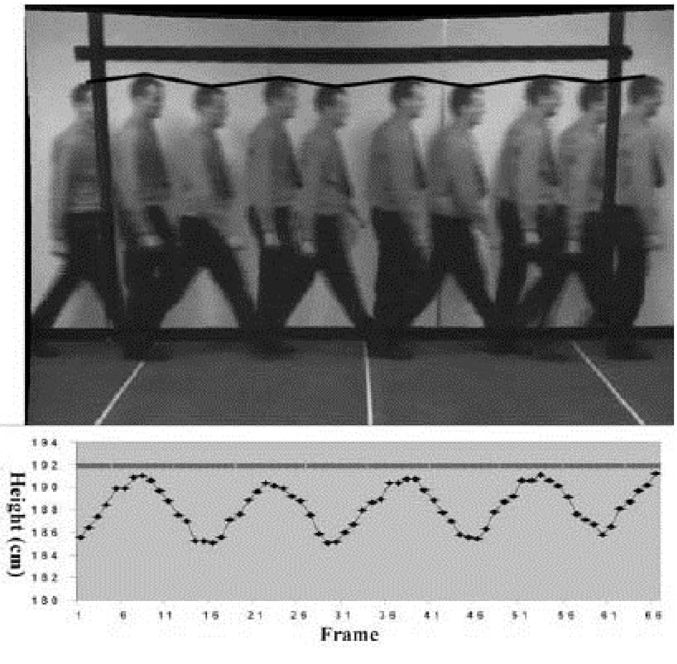

Fig. 8.28. The locomotion of the human with the trajectory of the scalp and the center of gravity of the body (Bramble, Compton a Klasén 2001).

In the first case, according to the dynamic stereotype, samples of human locomotion are shown, showing the course of the individual curves of the measured individual (Fig. 8.28), a diagram of movement skills and their reflection into the criminological traces (Figure 8.29), demonstrations of hip, knee and ankle angles (Fig. 8.29) and the angle (two-step) walking characteristics (Fig. 8.30).

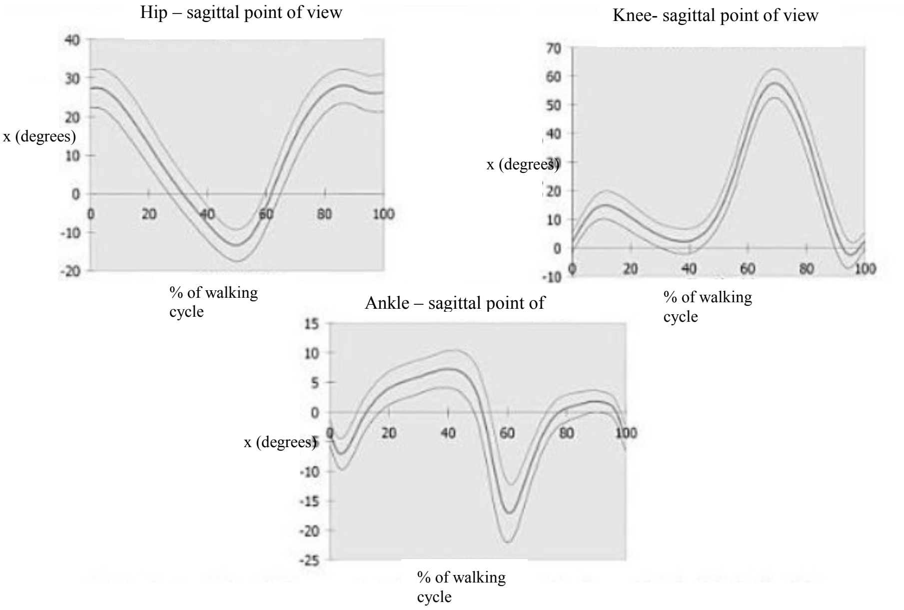

Fig. 8.29. Sample hip, knee and ankle angles in the sagittal plane; the middle curve in each graph is the average value of the upper and lower curves being the standard value of the maximum and minimum deviations from the mean (Porada, Rak 2007(a), (b)).

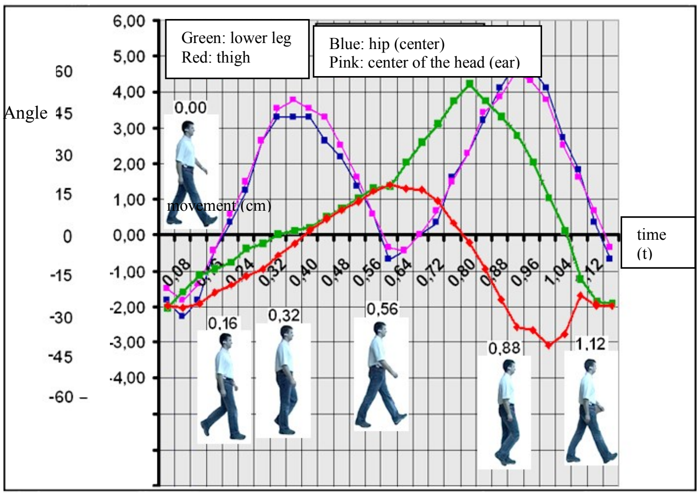

Fig. 8.30. Angular walking characteristics (two-stroke) depending on time (Straus, Jonák 2007).

In the latter case, the method is based on silhouettes, the method using the front-end recording (Goffredo, Carter, Nixon 2008). This method uses the front and top camera recording, which is usually a record that can be obtained from a publicly installed camera. The present method for walking analysis is divided into two basic steps :

a. walking cycle detection,
b. a description of the shape of the walking pattern,

and background images, walking cycle detection with periodic function, and walking volumes of two different people, for which there are also signed signatures that uniquely record the difference in walking of these two people (Fig. 8.31–8.34).

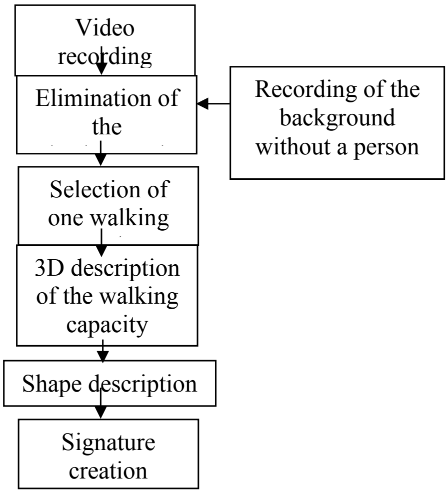

Fig. 8.31. Block scheme of the procedure (Goffredo, Carter, Nixon 2008).

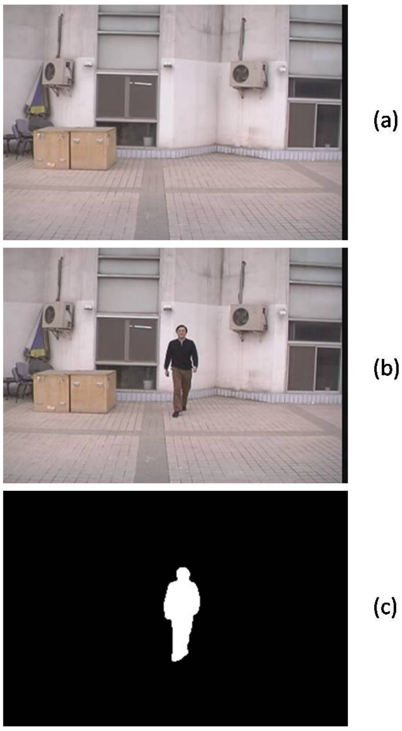

Fig. 8.32. a) Background image, b) background image with character and c) extracted characters (Goffredo, Carter, Nixon 2008).

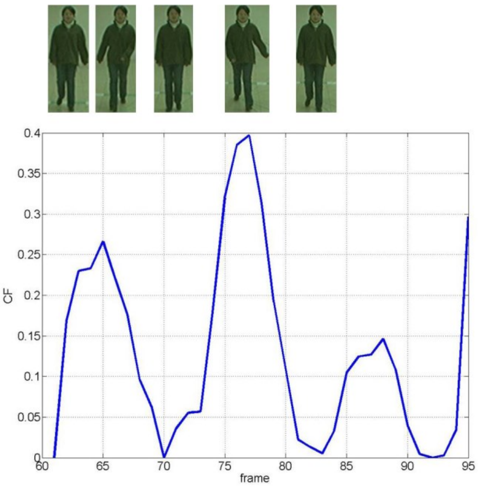

Fig. 8.33. Walk cycle detection with periodic function CF (Goffredo, Carter, Nixon 2008).

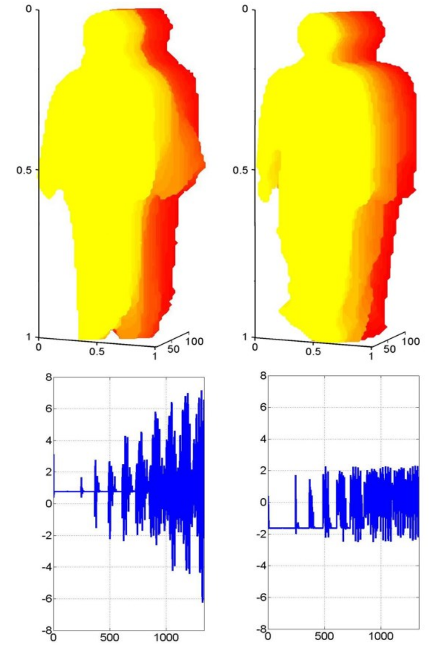

Fig. 8.34. Walking volumes for two different people (Goffredo, Carter, Nixon 2008).

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# Summary

Forensic Biomechanics is a young forensic science, its short axis of development has undergone a rapid expansion and the future appears to be a discipline that also, for example, will help to better and more intensive fighting crime. Forensic biomechanics solve issues and problems that can not be answered by any other forensic science.

Biomechanics is defined as the discipline that contributes to the solution of biological and medical problems, which include sub-problems and mechanical nature called “Biomechanical problems”. Their solutions are used insights, approaches, methods and theories of mechanics. Biomechanical problems are solved on the biomechanical objects that can have different character. These may be elements of the flora or fauna. In biomechanics it may be a technical object, in a different interaction with the human organism (implant fixator), or is itself the human organism as a whole, or its unseparated (in vivo), respectively separated part (in vitro).

Biomechanics is defined as an interdisciplinary science focused mainly on studying the mechanical structure and mechanical behaviour of living systems and their interactions with the environment.

Forensic biomechanics is the science which applies biomechanics and biomechanical methods for examining the investigative tracks with biomechanical content and decoding information from a forensically relevant events, which arose as a result of human activity and movement that relates to the investigation of the events. Forensic biomechanics explores and explains the circuit investigative tracks that have in themselves contained biomechanical content, thus described applications provide information on the human musculoskeletal system and its motion behaviour. Forensic biomechanics applied biomechanical principles to the problems occurring in the judicial practice, both civil and criminal law. Studying the mechanics of movement, particularly the movement of muscle control apparatus. Criminal procedure provides information on how this could lead to injuries during the violent attacks, suicides, murders and mass disasters, as well as whether the movement of people was feasible without foreign intervention. In the context of civil proceedings, it can be used to assess the falls without witnesses. Forensic biomechanics is based on physical principles and includes solutions using calculations, often with computer models.

Forensic biomechanics worth is being explored in joint biomechanics penetration and criminalistics. Creatively applies biomechanical examination methods, procedures and ways of solving the problems of biomechanics on criminolalistics. Forensic biomechanics studies and examines the musculoskeletal system and the physical behaviour of people who have a connection with the offense, leaving forensic clues that have in them encoded biomechanical content.

Subject Criminalistics like every other science is determined by a kind of studied the laws of the objective world. In the case of forensic biomechanics can define the subject of exploration in two directions. The subject of forensic biomechanics is examining forensic clues with biomechanical content and forensically relevant changes that resulted from mechanical interaction of “human-around”.

The book analysed the most frequent questions in the theory of forensic biomechanics.

Extensive measurements on large files has shown that physical height of the person is a significant length and width of bare feet, the length and width of the shoe length and width of the track shoes and can be relatively accurately calculated probable body height according to these parameters.

Mechanical extreme dynamic loads organism. These are typically situations where the attacker attacks the victim with punches, stick or other hard object. Most often, the attack is directed at the victim's head. In the case of these biomechanical analysis, an assessment of whether the contested person died immediately or some time survived and theoretically it would be possible to save her. In principle, it is important to identify and quantify important threshold for survival in extreme mechanical loads victim's head.

Biomechanical assessment of falls from a height of victims, most of them from windows of the house. Sometimes it happens that the aggressor attacked the victim and intended to kill by throwing out of the window and the investigation is prevented that fell victim by herself, or by some accident. Biomechanical analysis can assess whether the person dropped out alone, without foreign fault or whether it was at the moment of falling granted power pulse, and thus it had been fired (or could even bounce). It is to assess the geometry and kinematics of the centre of gravity in the fall as an open kinematic chain.

This publication is a close follow-up to the publication by Valenta, J. et al. (among others, V. Porada) Biomechanics. Praha: Academia 1985; Valenta, J. et al. (among others, V. Porada) Biomechanics, Clinical Aspects of Biomedicine, 2. Amsterdam - London – New York – Tokyo: Elsevier, 1993; Porada, V., Straus, J. Criminalistic and forensic Biomechanics. Praha: Police History, 2001; Valenta, J., Porada, V., Straus, J.: Biomechanics (Criminalistic and Forensic Applications), Prague: Police History, 2002; Valenta, J., Porada, V., Straus, J.: Biomechanics (Aspects of General and Forensic Biomechanics), Prague: Police History, 2003; Valenta, J., Porada, V., Straus, J.: Biomechanics. Aspects of General and Forensic Biomechanics (Criminalistic and Forensic Applications). Prague: Police History, 2004; Straus, J., Porada, V. Theory of Forensic Biomechanics. Prague: VŠFS, 2017.

The monograph "Forensic Biomechanics, Criminalistic and Forensic Applications of Biomechanics" was developed by standard, identifiable and scientifically recognized methodology of forensic science development. The book deals with a well-defined forensic biomechanics problems. The methodological basis is based on theoretical research so far and the scientific conclusions are oriented towards practical applications in criminal practice.

The monograph is the outcome of the research assignment of the Internal Grant Agency of VŠFS No. 7429/2017/07 entitled "New Possibilities of Investigating Forensic Footprints with Biomechanical Content and Interpretation of Conclusions of Expert Investigations" (a responsible researcher – J. Straus and a researcher – V. Porada).

# РЕЗЮМЕ

Судебная биомеханика - это молодая судебная наука, ее короткая ось развития претерпела быстрое расширение, и будущее, по-видимому, является дисциплиной, которая также, например, будет способствовать лучшей и более интенсивной борьбе с преступностью. Судебная биомеханика решает проблемы и проблемы, на которые не может ответить любая другая судебная наука.

Биомеханика определяется как дисциплина, которая способствует решению биологических и медицинских проблем, в том числе подсубъектов и механической природы, называемых «Биомеханические проблемы». В их решениях используются идеи, подходы, методы и теории механики. Биомеханические проблемы решаются на биомеханических объектах, которые могут иметь различный характер. Это могут быть элементы флоры или фауны. В биомеханике это может быть технический объект, в другом взаимодействии с человеческим организмом (фиксатор имплантата) или сам по себе человеческий организм в целом или его неразделенная (in vivo), соответственно разделенная часть (in vitro).

Биомеханика определяется как междисциплинарная наука, ориентированная главным образом на изучение механической структуры и механического поведения живых систем и их взаимодействия с окружающей средой.

Судебная биомеханика - это наука, которая применяет биомеханику и биомеханические методы для изучения следственных следов с биомеханическим контентом и информацией о декодировании из событий, имеющих отношение к событиям, которые возникли в результате человеческой деятельности и движения, которые связаны с исследованием событий. Судебная биомеханика исследует и объясняет следственные следственные цепи, которые сами по себе содержат биомеханическое содержание, поэтому описанные приложения предоставляют информацию о системе скелетно-мышечной системы человека и ее движении. Судебная биомеханика применяла биомеханические принципы к проблемам, возникающим в судебной практике, как гражданскому, так и уголовному праву. Изучение механики движения, в частности, движение мышечного контрольного аппарата. Уголовно-процессуальная процедура предоставляет информацию о том, как это может привести к травмам во время насильственных нападений, самоубийств, убийств и массовых бедствий, а также о том, возможно ли перемещение людей без вмешательства извне. В контексте гражданского судопроизводства его можно использовать для оценки падений без свидетелей. Судебная биомеханика основана на физических принципах и включает решения с использованием расчетов, часто с компьютерными моделями.

Судебная биомеханика стоит изучать в совместном проникновении биомеханики и криминалистики. Творчески применяет методы биомеханического исследования, процедуры и пути решения проблем биомеханики по криминалистике. Судебная биомеханика изучает и исследует костно-мышечную систему и физическое поведение людей, имеющих связь с преступлением, оставляя судебные подсказки, которые имеют в них закодированное биомеханическое содержание.

Предмет Криминалистики, как и всякая другая наука, определяется каким-то изучением законов объективного мира. В случае судебной биомеханики можно определить предмет исследования в двух направлениях. Предмет судебной биомеханики изучает криминалистические данные с биомеханическим контентом и сугубо значимые изменения, вызванные механическим взаимодействием «человека вокруг».

В книге проанализированы наиболее частые вопросы теории судебной биомеханики. Обширные измерения на больших файлах показали, что физическая высота человека составляет значительную длину и ширину босых ног, длину и ширину длины и ширины обуви для обуви и может быть относительно точно рассчитана вероятная высота тела в соответствии с этими параметрами ,

Механические экстремальные динамические нагрузки организма. Обычно это ситуации, когда атакующий атакует жертву ударами, палкой или другим жестким объектом. Чаще всего атака направлена на голову жертвы. В случае этих биомеханических анализов оценка того, умерла ли оспариваемая личность немедленно или какое-то время выжила, и теоретически ее можно было бы спасти. В принципе важно определить и количественно определить важный порог для выживания в экстремальных механических нагрузках головы жертвы.

Биомеханическая оценка падения с высоты жертв, большинство из них из окон дома. Иногда бывает так, что агрессор напал на жертву и намеревался убить, выбросив из окна, и расследование предотвратило, что жертва сама по себе или каким-то несчастным случаем. Биомеханический анализ может оценить, выпал ли человек отдельно, без посторонней ошибки или был ли он в момент падения поданного импульса мощности, и, таким образом, он был уволен (или даже мог отскочить). Оценить геометрию и кинематику центра тяжести осенью как открытую кинематическую цепь.

Эта публикация является близким наблюдением за публикацией Valenta, J. et al. (среди прочего, В. Порада) Биомеханика. Praha: Academia 1985; Valenta, J. et al. (среди прочего, В. Порада) Биомеханика, клинические аспекты биомедицины, 2. Амстердам-Лондон - Нью-Йорк - Токио: Элсевьер, 1993; Порада, В., Страус, Дж. Криминалистическая и судебная биомеханика. Прага: История полиции, 2001; Valenta, J., Porada, V., Straus, J.: Биомеханика (криминалистическая и судебная практика), Прага: история полиции, 2002; Valenta, J., Porada, V., Straus, J.: Биомеханика (аспекты общей и судебной биомеханики), Прага: история полиции, 2003; Valenta, J., Porada, V., Straus, J. Biomechanics. Аспекты общей и судебной биомеханики (криминалистическая и судебная практика. Прага: история полиции, 2004 г., Страус, Дж., Порада, В. Теория судебной биомеханики. Прага: VŠFS, 2017.

Монография «Судебная биомеханика, криминалистическое и судебно-медицинское применение биомеханики» была разработана стандартной, идентифицируемой и научно признанной методологией развития судебной науки. В книге рассматриваются четко определенные проблемы судебной биомеханики. Методологическая основа основана на теоретических исследованиях до сих пор, и научные выводы ориентированы на практическое применение в криминальной практике.

Монография является результатом исследовательского задания Агентства внутреннего гранта VŠFS № 7429/2017/07, озаглавленного «Новые возможности исследования судебных следов с биомеханическим содержанием и интерпретация выводов экспертных исследований» (ответственный исследователь - J. Straus и ресерхер - В. Порада).

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Prof. Porada is one of the foremost representatives of forensic science, with a wide background of knowledge of forensic engineering, forensic medicine, biomechanics and other related disciplines in the Czech and Slovak Republic. As an important scientific authority, he is also recognized abroad. His research is focused mainly on the area of theory and methodology of criminalistics, criminalistics theory and identification, criminalistics techniques and methodology of investigation of individual types of crimes. He is the founder of new research directions in forensic science, forensic biomechanics and police, and later in the security sciences. He has been Editor-in-Chief of the Karlovy Vary Law Review, a member of the Editorial Board of Criminalistics, Magazin for Experts, Forensic Engineering, Notitiae ex Academia Bratislavensi Iurisprudentiae, Košice security revue, State and Law, Crisis Management. He is currently working at the University of Finance and Administration in Prague, where he holds a fild in Security Science and at the same time is Deputy Editor-in-Chief of Forensic Science, Law, Criminalistics. He is also Editor-in-Chief of the European Science magazine and Vice-Chair of the European Association for Security EU.

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