HUMAN LOCOMOTION BIOMECHANICS

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Keywords: Loading, Performance, Kinematics, Force, EMG, Acceleration, Pressure, Modeling, Data Analysis.

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Summary

This chapter summarizes typical questions in human locomotion biomechanics and current approaches used for scientific investigation. The aim of the chapter is to (1) provide the reader with an overview of the research discipline, (2) identify the objectives of human locomotion biomechanics, (3) summarize current approaches for quantifying the effects of changes in conditions on task performance, and (4) to give an introduction to new developments in this area of research.

1. Introduction

Biomechanics may be defined as “The science that examines forces acting upon and within a biological structure and effects produced by such forces”. External forces, acting upon a system, and internal forces, resulting from muscle activity and/or external forces, are assessed using sophisticated measuring devices or estimations from model calculations. The possible results of external and internal forces are: Movements of segments of interest; Deformation of biological material and; Biological changes in tissue(s) on which they act. Consequently, biomechanical research studies/quantifies the movement of different body segments and the biological effects of locally acting forces on living tissue. Biomechanical research addresses several different areas of human and animal movement. It includes studies on (a) the functioning of muscles, tendons, ligaments, cartilage, and bone, (b) load and overload of specific structures of living systems, and (c) factors influencing performance. Questions are asked with respect to the effects of aging, health and disease and sports. As a consequence the populations of interest are highly varied, ranging from the young to the elderly, the disabled to the able bodied and athletes and non-athletes. Providing answers to questions in human
locomotion biomechanics is of interest to a range of professionals including sport scientists, sport equipment designers, coaches, athletes, physiotherapists, podiatrists and orthopedists. This chapter summarizes the key elements of human locomotion biomechanics. The information in this chapter has originally been covered in the books “Biomechanics of the Musculo-skeletal System” (Nigg and Herzog, 2007) and “Biomechanics of Sport Shoes” (Nigg, 2010).

2. Typical Questions in Locomotion Biomechanics

Questions in human locomotion biomechanics, outlined above, may be addressed through the description of the movement, studying the response of the human body to loading and investigating changes in performance. The feasibility of affecting loading and/or performance is of principal concern. Consequently, kinematics, kinetics, and muscle activity are studied to discover the factors responsible for the development of injury during physical activity and to improve performance in competition.

2.1. Description of Movement

Movement is described through the study of its kinematics, the geometry of motion without consideration of the forces that cause the motion. Nevertheless, it is important to realize that the cause of movement of a segment of interest is in fact the result of external and internal forces. This branch of biomechanics therefore studies and/or quantifies the movement of different body segments and factor that influence movement.

Movements of segments are generally described with references to anatomical planes of motion (e.g. the sagittal, coronal and transverse plane) and associated axes of rotation (e.g. the transverse, medial and longitudinal axis). This provides a reference frame for the description of the displacement of body segments in a three-dimensional space. A particular movement may furthermore be broken down into constituent phases. When comparing the heel-toe running and side-shuffle movements for example, it is possible to describe these movements with reference to the foot (Figure 1). Here, the ground contact phase of heel-toe running is initiated, when the heel of the foot contacts the ground. The forefoot then contacts the ground while the midfoot and heel roll inward. Following mid-stance, the heel leaves the ground while the foot rolls toward the outside. During a side-shuffle landing typically occurs on the forefoot while the rearfoot rotates with respect to the forefoot. The heel of the foot may contact the ground later. During takeoff, the foot again produces a relative rotation between the forefoot and the heel.

Based on such basic segmentation of a movement it then becomes possible to investigate the movement in greater detail. Important concepts for the description of the movement of the foot and lower leg during stance include movement coupling, foot torsion, and foot pronation and supination.

Movement coupling may be defined as the transfer of movement between segments through the action of muscle-tendon units and ligaments. Consequently, movement of one segment results in movement of one or more other segments. At the ankle joint for
example there is a transfer of movement between the lower leg and the foot. Such movement coupling is affected by:

- **Input movement**: High coupling occurs for inversion/eversion input movement from the foot (bottom-up) and low coupling for internal/external input movement from the lower leg (top-down).
- **Foot position**: Low coupling occurs when the foot is in dorsiflexion (heel-toe running) and high coupling when in plantarflexion (forefoot landing and most takeoff movements).
- **Ligaments**: Movement coupling increases when cutting ligaments on the lateral side and decreases when cutting ligaments on the medial side.

The distinction between the coupling from foot to lower leg (bottom-up) and the coupling from lower leg to foot (top-down) is important because during walking and running the lower leg experiences two opposite inputs. During initial ground contact, the input from the top (pelvis) corresponds to an external rotation of the leg. The input from the bottom (foot) corresponds to an internal rotation of the leg during initial ground contact.

![Figure 1. Illustration of heel-toe running (top) and side-shuffle movement (bottom).](image)

**Foot torsion** is defined as the rotation of the forefoot with respect to the rearfoot about a longitudinal foot axis. The conceptual idea of foot torsion has been developed to investigate negative effects of the loading of the locomotor system. The concept is illustrated in (Figure 2).

Most joints in the foot are not seen from the outside. Consequently, most biomechanical studies related to the human foot typically have not described rotations about a specific joint axis. Foot movement is often described with respect to axes that are easy to define in an experimental setting. The inward and outward rolling of the foot with respect to the ground or the leg is typically described using a “longitudinal foot axis” through the centre of the calcaneus and the centre of the second toe. Flexion in the forefoot with respect to the rest of the foot is often described using an “axis” through the five metatarsal heads. The inversion/eversion of the forefoot with respect to the rearfoot (i.e., foot torsion) is again described using a “longitudinal foot axis.”
Foot torsion seems to be important for economic movement, however, the optimal values for torsional stiffness are not currently known. Excessive torsional stiffness in a shoe is associated with negative effects with respect to the loading of the locomotor system. It is not known however, whether very low torsional stiffness would be beneficial from the point of view of injuries and/or performance.

Figure 2. Illustration of foot torsion when landing on an inclined plane: (A) barefoot with the heel touching the plane, (B) barefoot with the heel in the air for the whole ground contact, (C) with shoes with the heel touching the plane, and (D) with shoes with the heel in the air for the whole ground contact. This picture is a replication of results from initial high-speed films done by Stacoff and Kälin at the ETH Zurich in the mid-1980s.

Foot pronation and supination refer to rotations around the subtalar joint axis of the foot (inward and outward rolling of the rearfoot respectively) (Figure 3). Pronation and excessive pronation have been discussed extensively by the medical profession, athletes, and biomechanists. “Excessive” pronation has been stated as the reason for injuries, especially in running, and that “control” of foot pronation is important.

The ankle joint complex has two major functional axes: the subtalar joint axis between the talus and calcaneus, and the ankle joint axis between the talus and tibia (Figure 3). The position of the calcaneus and the tibia can be determined with acceptable accuracy. However, the position of the talus is hidden from the outside view. For the talus, the
orientation of and movement about the ankle and subtalar joint axes are difficult to determine (van den Bogert et al., 1994). For this reason, foot movement is often quantified about an anterior/posterior (inversion/eversion), a mediolateral (plantarflexion/dorsiflexion), and an inferior/superior (abduction/adduction) axis. These axes do not correspond to actual anatomical joints. They are called clinical axes. The clinical axes of the foot are easy to determine in real life and allow simple biomechanical measurements that are an indicator of pronation and supination. Eversion and inversion are used in almost all biomechanical studies related to sport shoes. In most cases, where authors use the term “pronation” or “supination,” their statements are based on measurements of eversion and inversion.

Figure 3. Illustration of the extrinsic muscle-tendon units crossing the ankle joint complex, and the functional axes of the subtalar and ankle joints.

It has been suggested that running injuries are associated with biomechanical factors such as “excessive impact loading” and “excessive pronation” (James et al., 1978; Clarke et al., 1983; Nigg et al., 1983; Nigg et al., 1987; Bates, 1989). However, there is little research to support the suggested correlation between abnormal positions of the foot and the development of pathology (Payne, 2007), or in general to support the notion that biomechanical factors are associated with the development of specific injuries.

2.2. Loading

Loading refers to the application of force to a structure. While force cannot be defined, it can be described with respect to its effects. Force application may affect displacement of body segments and affect biological structures (positively or negatively). The effects of force application have been investigated for a number of biological structures including bone, cartilage and muscle. The effects of forces may be instantaneous (e.g. bending, vibration, micro-fractures and fractures) or long term (micro- and macro-structural changes and structural damage). Due to the highly varied effects of loading and the number of structures affected by force application this is an ongoing topic in
human locomotion biomechanics that attracts attention from a number of research disciplines.

Impact forces result from the collision between two objects. Because collisions with other objects (or subjects) are common during physical activities, impact forces have been studied for many different sports. Studies have assessed the effects of crashing into the boards in ice hockey, heading of soccer balls, contacting the ball with a golf club to gain more distance and accuracy, and, of course, impact during landing on the ground in heel-toe running (Cavanagh, 1980; Cavanagh and Lafortune, 1980; Nigg and Denoth, 1980; Clarke et al., 1983a; Hamill et al., 1983; Frederick et al., 1984; Shorten et al., 1986; De Wit et al., 1995; Nigg, 1997; Kersting and Brüggemann, 1999; Milgrom et al., 2000; Shorten and Mientijes, 2003; Boyer and Nigg, 2007).

In human locomotion biomechanics, the assessment of forces between the foot and the ground are of particular interest. This interaction is typically assessed using the ground reaction force (GRF). In accordance with Newton’s third law of motion, the GRF is the force exerted by the ground on the foot, as the foot collides with the ground. Moreover, the GRF is a result of the accelerations of all segments of a body contacting the ground.

\[
\mathbf{F}_{\text{Ground}} (z) = \sum \mathbf{F}_{iz} = \sum m_i (\mathbf{a}_{iz} - \mathbf{g})
\]

where:
- \( \mathbf{F}_{\text{Ground}} (z) \) = resultant ground reaction force in vertical direction
- \( \mathbf{F}_{iz} \) = resultant force acting on segment \( i \) in vertical direction
- \( m_i \) = mass of segment \( i \)
- \( \mathbf{a}_{iz} \) = acceleration of the centre of mass of segment \( i \) in vertical direction
- \( \mathbf{g} \) = acceleration due to gravity (magnitude = \( g \))

Note: Vectors are shown in bold letters.

The GRF can be described in three-dimensions (Figure 4). The terms vertical, anterior/posterior and medial/lateral are used to describe force components in relation to the orientation of the foot on the ground. Furthermore, the terms normal force and shear force are used to describe a force that is applied perpendicular to the surface of interest (normal force) and a force that is applied parallel to the surface of interest (shear force).

GRFs acting on the human locomotor system may be divided into two types: low frequency “active” forces, and high frequency “impact” forces (Figure 5). “Active” is used to indicate that the whole movement is controlled through muscle activity, and that muscles can and do change their activity to control the movement (Nigg, 1978). “Impact” is used to indicate the first impact peak where muscular control of the landing movement is limited (Frederick et al., 1981). Here the muscles are pre-activated to prepare for the expected landing, and do not change their activity during the initial phase as a result of unexpected changes of movement conditions. These observations lead to a further definition of impact forces: forces, resulting from the collision of two
objects, that reach their maximum earlier than 50 milliseconds after first contact of the two objects.

Figure 4. Illustration of the vertical and horizontal impact peaks in the ground reaction force time curves for one subject; 10 trials running 4 m/s.

Figure 5. Vertical ground reaction force for a two-legged vertical jump with takeoff and landing at the same location. (Adapted from Nigg, 1978.)

Experimental measurements and modeling studies have been performed to identify and verify the segmental contributors to the magnitude of the impact force. A model by Bobbert et al. (Bobbert et al., 1991), using a model of the human body that consists of seven rigid segments: two feet, two lower legs, two upper legs, and the rest of the body (trunk, arms, and head), confirmed experimental measurements showing that the impact force depends upon:

- The contribution of the deceleration of the rest of the body
- The deceleration of the support foot
- The deceleration of the lower support leg
- The deceleration of the upper support leg
The relative contributions vary with running style. In heel-toe running, the magnitude of the impact peak of the GRF is determined by the deceleration of the stance leg and the acceleration of the trunk and the swing leg. In heel-toe running, the frequency content of the impact peak of the GRF is determined primarily by the deceleration of the supporting foot and leg segments.

During impact, external impact forces are influenced by the “effective mass” (i.e. the mass that is primarily involved in the initial deceleration process and is decelerated to a zero velocity during impact). In running with heel landing, the effective mass consists of the foot and, depending on the running style, part of the leg. The effective mass for heel landing in running has been estimated at between 5 and 15 kg (Denoth, 1986). It is relatively high for a knee angle close to 180 degrees during landing and smaller when the knee is more bent. In running with forefoot landing, the effective mass consists of the forefoot and part of the foot, and is much smaller than for heel landing. Assuming that the deceleration of the effective mass is of similar magnitude, the impact force for running with forefoot landing must be much smaller than for running with heel landing. This leads to the conclusion that impact forces in the ankle joint are about the same order of magnitude for toe and for heel landing. Therefore, changing for example from heel-toe to forefoot landing will not provide a reduction in general ankle joint loading. Furthermore, landing on the forefoot will produce additional forces in the Achilles tendon.

2.3. Performance

The performance of an individual may be affected by managing the energy involved in a particular movement task. Energy management requires equipment capable of storing, returning, and maybe even enhancing energy. Performing this energy management requires understanding of the laws of nature with respect to work and energy. Work, energy and performance during physical activities depend on biochemical, physiological, thermodynamic, and mechanical factors. An athlete’s performance in a running competition depends on a number of physiological, biomechanical and psychological variables. Biomechanical influencing factors include the resulting mechanical work and energy. Aspects of work and energy during locomotion, physical exercise, and sport have been discussed in many studies (Fenn and Morrison, 1930; Elftman, 1939; Cavagna et al., 1976; Winter, 1978; Cavanagh and Williams, 1982; Clement et al., 1982; Frederick et al., 1983; Williams, 1985; Aleshinsky, 1986; di Prampero, 1986; Nigg and Anton, 1995; Stefanyshyn and Nigg, 1998a).

Work is defined as the amount of energy transferred by a force. It is a scalar unit expressed in the unit joules (J). The mechanical work, \( W \), performed by a force vector, \( \mathbf{F} \), acting on a particle is defined as the line integral:

\[
W = \int \mathbf{F} \cdot d\mathbf{r}
\]

Unit of work:

\[
[W] = [\text{force}] \cdot [\text{distance}] \quad \text{in N} \cdot \text{m} = \text{Joule} = \text{J}
\]
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**Biographical Sketches**

**Dr. Benno M. Nigg** is a past president of the International Society of Biomechanics and a founding Member of the World Council of Biomechanics. He is the recipient of the Career Award from the Canadian Society for Biomechanics and the Hay Award from the American Society of Biomechanics. His research interests are centered on human locomotion: the forces acting on and within the locomotor system and the effects produced by these forces. The primary emphasis of his research is on mobility and longevity and the application of his research findings to clinical practice and the development of movement related products such as orthoses, shoe insoles and sport shoes. Dr. Nigg has strong collaborations with a series of academic partners (Federal Technical Institute Zurich, Max Planck Institute Berlin, University of Erlangen, Universities of Salzburg and Innsbruck from which he received honorary doctoral degrees, University of Basel and University of Remagen) and non-academic partners including: adidas Germany and USA, Masai Technology (Switzerland), the International Olympic Committee (Medical Commission) and Iowa Germany.

**Gregor Kuntze** is a Research Associate and Adjunct Professor at the Faculty of Kinesiology, University of Calgary, and acts as an Associate Investigator with the Alberta Children’s Hospital Research Institute, Cumming School of Medicine, University of Calgary. His primary research focus is on paediatric rehabilitation with a specialization in clinical biomechanics and motor control. After completing a Ph.D. in Biomechanics and Physiology at Loughborough University, England, he conducted postdoctoral work on on-body sensing systems in Wales, UK, before joining the Human Performance Laboratory, University of Calgary, Canada. At the HPL he developed novel methods for the investigation of multi-muscle activation changes. He joined the Department of Mechanical and Manufacturing Engineering in 2012 where he developed novel methods for the in-vivo investigation of movement and cartilage loading mechanics abnormality in the ligament deficient and osteoarthritic knee joint. These methods involve motion analysis, high-speed biplanar video-radiography, electromyography and biomedical imaging. His current work as Research Associate at the Faculty of Kinesiology focuses on the application of interdisciplinary research approaches to clinical pediatrics populations and the evaluation of clinical interventions and rehabilitation.