HUMAN LOCOMOTION BIOMECHANICS

B. M. Nigg,
Human Performance Laboratory, University of Calgary, Calgary, Canada

G. Kuntze,
Faculty of Kinesiology, University of Calgary, Calgary, Canada

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Contents

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.

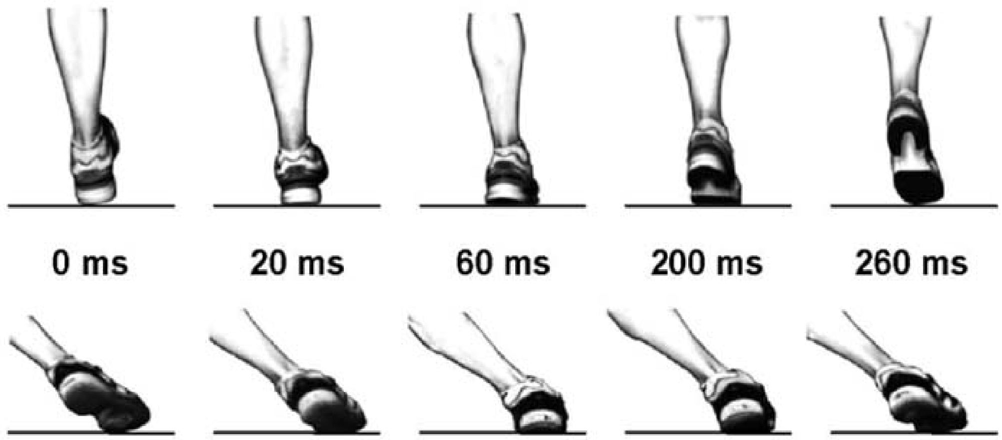

Figure 1. Illustration of heel-toe running (top) and side-shuffle movement (bottom).

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.

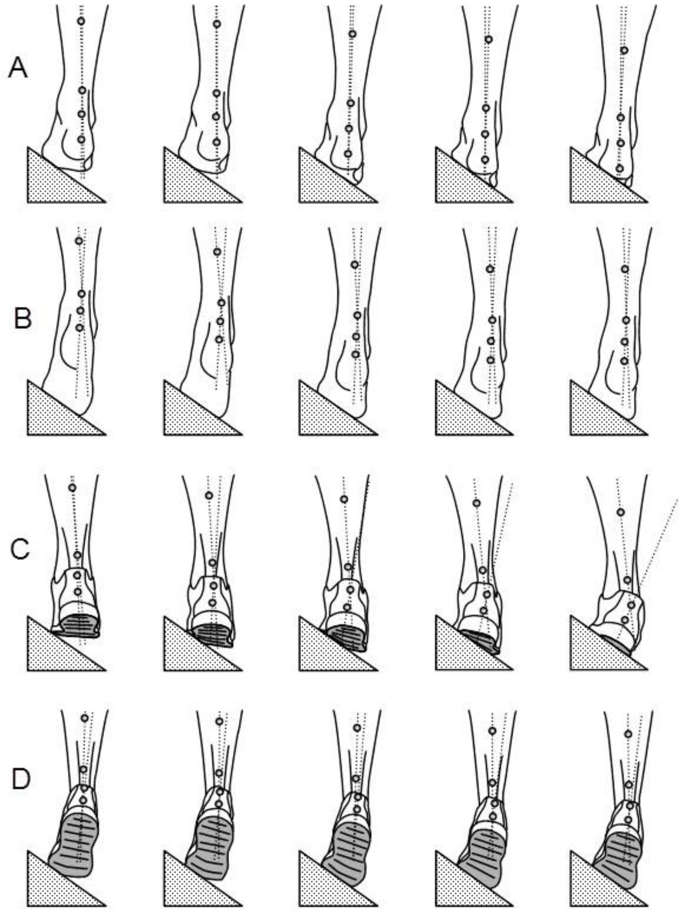

Figure 2. Illustration of foot torsion when landing on an inclined plane: (A) barefoot with the heel touching the plane, (B) barefoot with the heel in the air for the whole ground contact, (C) with shoes with the heel touching the plane, and (D) with shoes with the heel in the air for the whole ground 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.

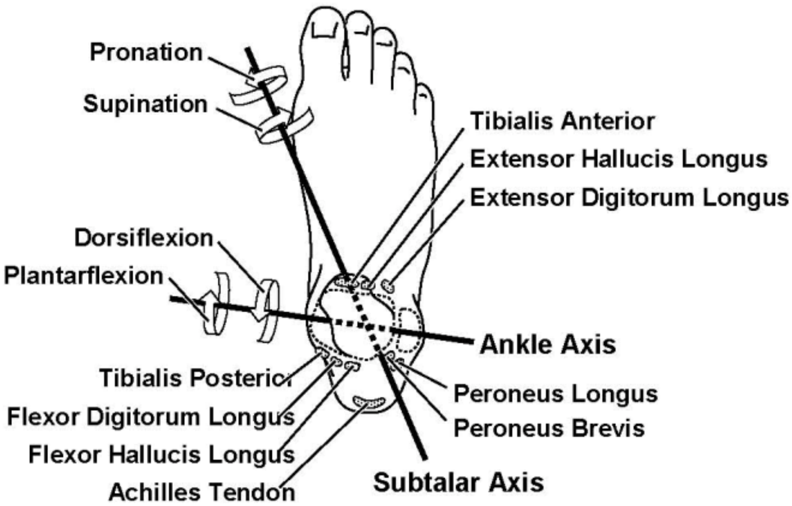

Figure 3. Illustration of the extrinsic muscle-tendon units crossing the ankle joint complex, and the functional axes of the subtalar and ankle joints.

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.

$$\mathbf{F}_{\text{Ground}}(z) = \sum \mathbf{F}_{iz} = \sum \mathrm{m}_i\left(\mathbf{a}_{iz} - \mathbf{g}\right)$$

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.

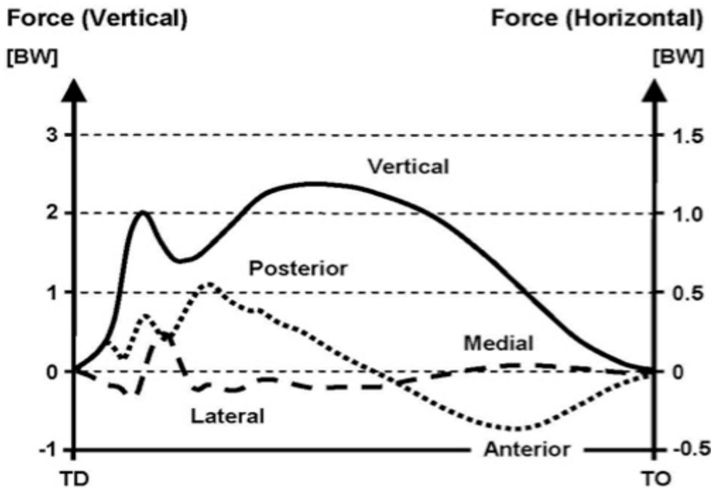

Figure 4. Illustration of the vertical and horizontal impact peaks in the ground reaction force time curves for one subject; 10 trials running 4 m/s.

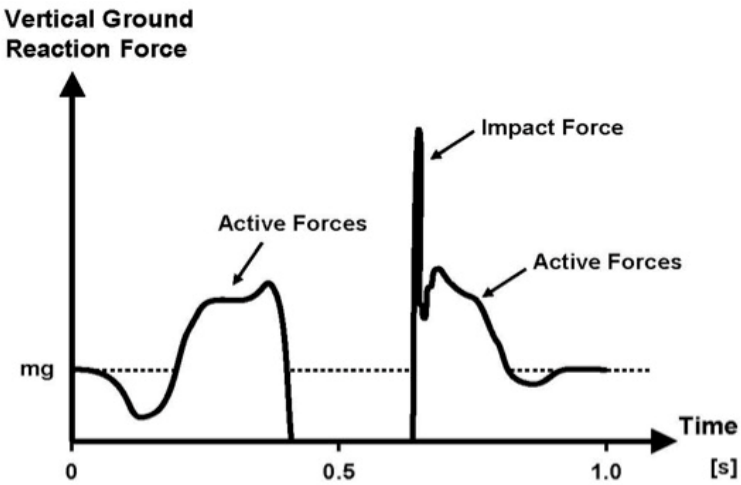

Figure 5. Vertical ground reaction force for a two-legged vertical jump with takeoff and landing at the same location. (Adapted from Nigg, 1978.)

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:

$$\mathrm{W} = \int \mathbf{F} \bullet d\mathbf{r}$$

Unit of work:

$$[W] = [\text{force}] \bullet [\text{distance}] \text{ in N} \cdot \text{m} = \text{Joule} = \text{J}$$

Bibliography

Abdel-Aziz, Y.I. & Karara, H.M. (1971). Direct linear transformation from comparator co-ordinates into object space co-ordinates. In Proc. ASP/UI Symposium On Close-range Photogrammetry. *Am. Soc. Of Photogrammetry*. pp. 1–18. [A description of the basis of image calibration using DLT].

Aldroubi, A. & Unser, M. (1996). *Wavelets in Medicine and Biology*, New York: CRC Press. [An expert's guide on the application of wavelet analysis in medicine and biology].

Aleshinsky, S.Y. (1986). An energy "sources" and "fractions" approach to the mechanical energy expenditure problem--I. Basic concepts, description of the model, analysis of a one-link system movement. *Journal of Biomechanics*, 19(4), 287–93. [Basic concepts and applications for mechanical energy problems].

Alexander, R.M. & Bennet-Clark, H.C. (1977). Storage of elastic strain energy in muscle and other tissues. *Nature*, 265(5590), 114–7. [An explanation of the concepts of strain energy storage in soft tissues].

Alexander, R.M. & Vernon, A. (1975). The mechanics of hopping by kangaroos (Macropodidae). *Journal of Zoology*, 177(2), 265–303. [An example of the advantages of energy storage for an animal model].

Alexander, R.M. (1988). *Elastic Mechanisms in Animal Movement*, Cambridge University Press. [A summary of the contribution of elastic mechanisms to animal locomotion].

Anderson, F.C. & Pandy, M.G. (2001). Dynamic optimization of human walking. *Journal of Biomechanical Engineering*, 123(5), 381. [Human gait simulation using minimum energy expenditure].

Aritomi, H., Morita, M. & Yonemoto, K. (1983). A simple method of measuring the footsole pressure of normal subjects using prescale pressure-detecting sheets. *Journal of Biomechanics*, 16(2), 157–65. [An fundamental manuscript on the in-vivo measurement of foot pressure distribution].

Asang, E. (1974). Biomechanics of the Human Leg in Alpine Skiing. In R. C. Nelson & C. A. Morehouse, eds. *Biomechanics IV*. Baltimore: University Park Press, pp. 236–242. [A study of tibial strain in skiing].

Asmussen, E. & Bonde-Petersen, F. (1974). Apparent efficiency and storage of elastic energy in human muscles during exercise. *Acta physiologica Scandinavica*, 92(4), 537–45. [An evaluation of the utilization of elastic energy in humans].

Basmajian, J.V. & De Luca, C.J. (1985). *Muscles Alive. Their Functions Revealed by Electromyography* 5th ed., Baltimore: Williams & Wilkins. [A discussion of the use of EMG to study the function skeletal muscles].

Bates, B.T. (1989). Comment on "The influence of running velocity and midsole hardness on external impact forces in heel-toe-running". *Journal of Biomechanics*, 22(8-9), 963–5. [A study investigating the relationship between impact force and injury].

Bauman, J.H. & Barnd, P.W. (1963). Measurement of pressure between foot and shoe. *JAMA: The Journal of the American Medical Association*, 184(9), 164. [A methodology for the evaluation of foot pressure when wearing shoes].

Biewener, A. & Baudinette, R. (1995). In vivo muscle force and elastic energy storage during steady-speed hopping of tammar wallabies (Macropus eugenii). *The Journal of Experimental Biology*, 198(Pt 9), 1829–41. [An example of the advantages of energy storage for an animal model].

Biewener, A. (1998). Muscle-tendon stresses and elastic energy storage during locomotion in the horse. *Comparative Biochemistry and Physiology. Part B, Biochemistry & Molecular Biology*, 120(1), 73–87. [An example of the advantages of energy storage for an animal model].

Bigland, B. & Lippold, O.C. (1954). Motor unit activity in the voluntary contraction of human muscle. *The Journal of Physiolog*y, 125(2), 322–35. [A key reference of the neuromuscular mechanisms of muscle activations].

Bigland-Ritchie, B., Donovan, E.F. & Roussos, C.S. (1981). Conduction velocity and EMG power spectrum changes in fatigue of sustained maximal efforts. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 51(5), 1300–5. [An evaluation of the effects of fatigue on the neuromuscular system].

Bishop, P.J. & Briard, B.D. (1984). Impact performance of bicycle helmets. *Canadian Journal of Applied Sport Sciences. Journal canadien des sciences appliquées au sport*, 9(2), 94–101. [A study of the effects of body worn equipment to mitigate impact forces].

Bishop, P.J., Norman, R.W. & Kozey, J.W. (1984). An evaluation of football helmets under impact conditions. *The American Journal of Sports Medicine*, 12(3), 233–6. [A study of the effects of body worn equipment to mitigate impact forces].

Bobbert, M.F., Schamhardt, H.C. & Nigg, B.M. (1991). Calculation of vertical ground reaction force estimates during running from positional data. *Journal of Biomechanics*, 24(12), 1095–1105. [An investigation of the contributions of body segments on the vertical ground reaction force].

Van den Bogert, A.J., Smith, G.D. & Nigg, B.M. (1994). In vivo determination of the anatomical axes of the ankle joint complex: An optimization approach. *Journal of Biomechanics*, 27(12), 1477–1488. [This study represents work to optimize estimates of joint kinematics at the multi-articulate ankle joint].

Bouisset, S. & Goubel, F. (1971). Interdependence of relations between integrated EMG and diverse biomechanical quantities in normal voluntary movements. *Activitas Nervosa Superior*, 13(1), 23–31. [An investigation of EMG magnitude and muscle force generation].

Boyer, K.A. & Nigg, B.M. (2007). Changes in muscle activity in response to different impact forces affect soft tissue compartment mechanical properties. *Journal of Biomechanical Engineering*, 129(4), 594–602. [An evaluation of the concepts of muscle tuning].

Boyer, K.A. & Nigg, B.M. (2004). Muscle activity in the leg is tuned in response to impact force characteristics. *Journal of Biomechanics*, 37(10), 1583–1588. [An evaluation of the concepts of muscle tuning].

Boyer, K.A. & Nigg, B.M. (2006). Soft tissue vibrations within one soft tissue compartment. *Journal of Biomechanics*, 39(4), 645–51. [An evaluation of the concepts of muscle tuning].

Breyer, H.G., Enes-Gaiao, F. & Kuhn, H.J. (1979). Biegebeanspruchung des Femurkopfprosthesenschaftes bei hypertrochanter Osteotomie. In Proceedings: Pauwels Symposium. Berlin: Free University Berlin. [This study assesses the deformation characteristics of the hip replacement components].

Calderale, P.M., Gola, M.M. & Gugliotta, A. (1979). New Theoretical and Experimental Developments in the Mechanical Design of Implant Stems of Stem-femur Coupling: New Improved Procedures. In Proceedings: Pauwels Symposium. Berlin: Free University Berlin, pp. 199–208. [A study on the mechanical requirements for joint prosthesis].

Calderale, P.M. (1983). The use of strain gauges for biometrics in Europe. *Engineering in Medicine*, 12(3), 117–33. [An early summary of the methodologies of strain assessment].

Van Campen, D.H., Croon, H.W. & Lindwer, J. (1979). Mechanical loosening of knee-endoprostheses intermedullary stems: influence of dynamic loading. In Proceedings 25th Annual ORS. pp. 20–22. [The study describes the effects of joint loading during motion on the integrity of the prosthesis – bone interface].

Cavagna, G.A., Dusman, B. & Margaria, R. (1968). Positive work done by a previously stretched muscle. *Journal of Applied Physiology*, 24(1), 21–32. [This study provides data on the concept of positive muscular work].

Cavagna, G.A., Thys, H. & Zamboni, A. (1976). The sources of external work in level walking and running. *The Journal of Physiology*, 262(3), 639–57. [This paper reviews the sources of external work].

Cavanagh, P.R. & Ae, M. (1978). A technique for the display of pressure paths from a force platform. *Journal of Biomechanics*, 11, 487–491. [A methodology for the visualization of foot pressure data].

Cavanagh, P.R. & Lafortune, M.A. (1980). Ground reaction forces in distance running. *Journal of Biomechanics*, 13(5), 397–406. [A review of the change in force data during running].

Cavanagh, P.R. & Williams, K.R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*, 14(1), 30–5. [An integrated biomechanics and physiology study to evaluate the relationship between movement and resultant energy demands].

Cavanagh, P.R. et al. (1983). A New Device for the Measurement of Pressure Distribution Inside the Shoe. In H. Matsui & K. Kobayashi, eds. Biomechanics VIII-B. Champaign, IL: *Human Kinetics*, pp. 1089–1096. [A methodology for improved foot pressure assessment].

Cavanagh, P.R. (1980). *The Running Shoe Book*, Mountain View, CA: Anderson World, Inc. [A comprehensive review of the history and development of running shoes].

Chu, M.L., Yazdani-Ardakani, S., Gradisar, I.A. & Askew, M.J. (1986). An in vitro simulation study of impulsive force transmission along the lower skeletal extremity. *Journal of Biomechanics*, 19(12), 979–87. [A simulation study of impulse force transmission].

Clarke, T.E., Frederick, E.C. & Cooper, L.B. (1983a). Biomechanical measurements of running shoe cushioning properties. In B. M. Nigg & B. A. Kerr, eds. *Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary: University of Calgary Press, pp. 25–33. [A comprehensive review of methodologies and observations on the effects of footwear cushioning].

Clarke, T.E., Frederick, E.C. & Cooper, L.B. (1983b). Effects of shoe cushioning upon ground reaction forces in running. *International Journal of Sports Medicine*, 4(4), 247–51. [An assessment of the effects of footwear cushioning].

Clarke, T.E. (1980). *The Pressure Distribution under the Foot during Barefoot Walking*. Pennsylvania State University, University Park, PA. [A historical study of dynamic pressure distribution].

Clement, D.B. Taunton, J.E., Wiley, J.P., Smart, G. W. & McNicol, K.L. (1982). Investigation of metabolic efficiency in runners with and without corrective orthotic devices. *International Journal of Sports Medicine*, 2, 14–15. [A study of the effects of footwear on energy demands].

Conforto, S., D'Alessio, T. & Pignatelli, S. (1999). Optimal rejection of movement artefacts from myoelectric signals by means of a wavelet filtering procedure. *Journal of Electromyography and Kinesiology*, 9(1), 47–57. [A novel methodology for the improved filtering of electromyographic data].

Crowninshield, R.D. & Tolbert, J.R. (1983). Cement strain measurement surrounding loose and well-fixed femoral component stems. *Journal of Biomedical Materials Research*, 17(5), 819–28. [An assessment of surgical procedure on strain prosthesis strains].

Dempster, W.T. (1961). Free Body Diagrams as an Approach to the Mechanics of Human Posture and Motion. In F. G. Evans, ed. *Biomechanical Studies Of The Musculo-skeletal System*. Springfield, IL: Thomas, pp. 81–135. [A foundation chapter on the application of ridged body mechanics to the study of human motion].

Denoth, J. (1986). Load on the Locomotor System and Modeling. In B. M. Nigg, ed. *Biomechanics of Running Shoes*. Champaign, Illinois: Human Kinetic Publishers, pp. 63–116.

Doud, J.R. & Walsh, J.M. (1995). Muscle fatigue and muscle length interaction: effect on the EMG frequency components. *Electromyography and Clinical Neurophysiology*, 35(6), 331–9. [An evaluation of the changes in the muscle EMG due to fatigue].

Dul, J., Johnson, G.E., Shiavi, R. & Townsend, M.A. (1984). Muscular synergism--II. A minimum-fatigue criterion for load sharing between synergistic muscles. *Journal of Biomechanics*, 17(9), 675–84. [An explanation of the concept of combined activity of multiple muscles and the effects on load sharing].

Elftman, H. (1934). A cinematic study of the distribution of pressure in the human foot. *The Anatomical Record*, 59(4), 481–491. [A historical reference of the study of foot pressure].

Elftman, H. (1939). Forces and energy changes in the leg during walking. *American Journal of Physiology*, 125, 339–356. [A historical reference of biomechanics analysis].

Elliott, B.C., Blanksby, B.A. & Ellis, R. (1980). Vibration and rebound velocity characteristics of conventional and oversized tennis rackets. *Research Quarterly for Exercise and Sport*, 51(4), 608–615. [An evaluation of sports equipment design on resultant mechanical properties].

Farina, D., Merletti, R. & Enoka, R.M. (2004). The extraction of neural strategies from the surface EMG. *Journal of Applied Physiology*, 96(4), 1486–95. [A review of the use of EMG to identify neuromuscular function].

Fenn, W.O. & Morrison, C.A. (1930). Frictional and kinetic factors in the work of sprint running. *American Journal of Physiology*, 92, 583–611. [An early analysis of sports performance].

Fischbein, E. (1987). *Intuition in Sciences and Mathematics*, Dordrecht, Netherlands: D. Reidel Publishing Company. [A detailed summary of the concept and development of intuition]

Frederick, E.C., Clarke, T.E. & Hamill, C.L. (1984). The effect of running shoe design on shock attenuation. In E.C. Frederick, ed. *Sport Shoes and Playing Surfaces*. Champaign, Illinois: Human Kinetic Publishers, pp. 190–198. [A summary of knowledge on the effects of footwear design on impact forces].

Frederick, E.C., Hagy, J.L. & Mann, R.A. (1981). The prediction of vertical impact force during running. *Journal of Biomechanics*, 14(7), 498. [An investigation into the relationship between running mechanics and impact force].

Frederick, E.C., Clarke, T.E., Larsen, L.J. & Cooper, L.B. (1983). The effects of shoe cushioning on the oxygen demands of running. In B.M. Nigg & B. Kerr, eds. *Biomechanical Aspects of Sport Shoes and Playing Surfaces*. Calgary, AB.: University of Calgary Press, pp. 107–114. [A summary of the link between footwear and metabolic energy costs].

Gootzen, T.H., Stegeman, D.F. & Van Oosterom, A. (1991). Finite limb dimensions and finite muscle length in a model for the generation of electromyographic signals. *Electroencephalography and Clinical Neurophysiology*, 81(2), 152–62.

Gross, T.S. & Nelson, R.C. (1988). The shock attenuation role of the ankle during landing from a vertical jump. *Medicine and Science in Sports and Exercise*, 20(5), 506–14. [This article provides a detailed description of the role of the ankle during multi-joint load attenuation strategies].

Grundy, M., Tosh, P.A., McLeish, R.D. & Smidt, L. (1975). An investigation of the centres of pressure under the foot while walking. *The Journal of Bone and Joint Surgery. British volume*, 57(1), 98–103. [A detailed analysis of dynamic foot pressure].

Hagberg, M. (1981). Muscular endurance and surface electromyogram in isometric and dynamic exercise. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 51(1), 1–7. [A study of neuromuscular adaptations to fatigue].

Hamill, J., Bates, B.T., Knutzen, K.M. & Sawhill, J.A. (1983). Variations in ground reaction force parameters at different running speeds. In *Human Movement Sciences* 2 (1-2). 47–56. [An investigation of biomechanical alterations in running].

Hatze, H. (1976). The complete optimization of a human motion. *Mathematical Biosciences*, 28(1-2), 99–135. [An early simulation study of human motion].

Hauser, W. & Schaff, P. (1987). Ski boots: biomechanical issues regarding skiing safety and performance. *International Journal of Sport Biomechanics*, 3, 326–344. [An investigation of pressure distribution in a ski boot].

Hehne, H.J. (1983). *Das Patellofemoralgelenk*, Stuttgart: Enke Verlag. [A book summarizing knowledge of the patellofemoral joint].

Hennig, E.M. & Milani, T.L. (1995). In-shoe pressure distribution for running in various types of footwear. *Journal of Applied Biomechanics*, 11(3), 299–310. [A study of pressure distributions in different running shoes].

Hennig, E.M., Cavanagh, P.R., Albert, H.T. & Macmillan, N.H. (1982). A piezoelectric method of measuring the vertical contact stress beneath the human foot. *Journal of biomedical engineering*, 4(3), 213–22. [An investigation of pressure distributions].

Herzog, W. & Leonard, T.R. (1991). Validation of optimization models that estimate the forces exerted by synergistic muscles. *Journal of Biomechanics*, 24 Suppl 1, 31–9. [A validation study of a musculoskeletal model].

Herzog, W. (1987). Individual muscle force estimations using a non-linear optimal design. *Journal of Neuroscience Methods*, 21(2-4), 167–79. [A study on the validation of model derived muscle force estimates].

Hsiao, H., Guan, J. & Weatherly, M. (2002). Accuracy and precision of two in-shoe pressure measurement systems. *Ergonomics*, 45(8), 537–55. [This research identified that capacitive sensing technologies are generally more accurate than resistive sensing systems].

Huiskes, R. & Sloof, T.J. (1979). Experimentelle und rechnerische Spannungsanalyse der Hüftgelenkverankerung. In Proceedings: Pauwels Symposium. Berlin: Free University Berlin, pp. 173–198. [An in-vitro stress analysis of the hip joint].

Huiskes, R. (1980). Some fundamental aspects of joint replacement. *Acta Orthopaedica Scandinavica*, Suppl. 185. [A review of joint mechanics to inform joint replacement surgery].

Hunter, I.W., Kearney, R. & Jones, L.A. (1987). Estimation of the Conduction Velocity of Muscle Action Potentials using Phase and Impulse Response Function Techniques. *Medical & Biological Engineering & Computing*, 25(2), 121–126. [An investigation of the basic mechanisms of muscular nerve impulses].

Hutton, W.C. & Dhanendran, M. (1981). The mechanics of normal and hallux valgus feet--a quantitative study. *Clinical Orthopaedics and Related Research*, (157), 7–13. [An investigation of the mechanics of foot mal-alignment].

Van Ingen Schenau, G.J. (1984). An alternative view of the concept of utilisation of elastic energy in human movement. *Human Movement Science*, 3(4), 301–336. [A study investigating the concept of energy storage and return in humans].

Jacob, H.A.C. & Huggler, A.H. (1979). Spannungsanalysen an Kunststoffmodellen des menschlichen Beckens sowie des proximalen Femurendes mit und ohne Prothese. In Proceedings: Pauwels Symposium. Berlin: Free University Berlin, pp. 118–135. [An investigation of the stresses in the human pelvis and hip and the consequences of joint replacement].

James, S.L., Bates, B.T. & Osternig, L.R. (1978). Injuries to runners. *The American Journal of Sports Medicine*, 6(2), 40–50. [A review of the concepts of movement mechanics and running injuries].

Karhunen, K. (1947). Über lineare Methoden in der Wahrscheinlichkeitsrechnung. In *Annales Academiae Scientiarum Fennicae. Series A1: Mathematica-Physica*. pp. 3–79. [A comprehensive summary of the concepts underlying principal component analysis].

Karlsson, S. & Gerdle, B. (2001). Mean frequency and signal amplitude of the surface EMG of the quadriceps muscles increase with increasing torque — a study using the continuous wavelet transform. *Journal of Electromyography and Kinesiology*, 11(2), 131–140. [An investigation of EMG changes with increasing muscular force generation].

Karlsson, S., Yu, J. & Akay, M. (2000). Time-frequency analysis of myoelectric signals during dynamic contractions: a comparative study. *IEEE transactions on Bio-medical Engineering*, 47(2), 228–38. [A wavelet transformation approach to studying muscular activations].

Kemeny, J.G. (1961). *A Philosopher Looks at Science*, D.Van Nostrand co. [A review of the philosophical problems of science and the scientific method]

Kersting, U.G. & Brüggemann, G. (1999). Adaptation of the human calcaneus to variations of impact forces during running. *Clinical Biomechanics* (Bristol, Avon), 14(7), pp.494–503. [An investigation of the effects of impact forces].

King, A.I. Ruan, J.S., Zhou, C., Hardy, W.N. and Khalil, T.B. (1995). Recent advances in biomechanics of brain injury research: a review. *Journal of Neurotrauma*, 12(4), 651–8. [The development of tolerances of head impacts with respect to brain injuries].

Komi, P.V. & Tesch, P. (1979). EMG frequency spectrum, muscle structure, and fatigue during dynamic contractions in man. *European Journal of Applied Physiology and Occupational Physiology*, 42(1), 41–50. [A detailed assessment of muscle structure and function].

Komi, P.V., Salonen, M., Järvinen, M. & Kokko, O. (1987). In vivo registration of Achilles tendon forces in man. I. Methodological development. *International Journal of Sports Medicine*, 8 Suppl 1, 3–8. [A study on the in-vivo assessment of tendon forces].

Lafortune, M.A. & Cavanagh, P.R. (1987). Three-dimensional Kinematics of the Patella During Walking. In B. Jonsson, ed. Biomechanics X-A. Champaign, IL: *Human Kinetics*, pp. 337–341. [A retailed review of the movement patterns of the patella in walking].

Lafortune, M.A. & Hennig, E.M. (1991). Contribution of angular motion and gravity to tibial acceleration. *Medicine and Science in Sports and Exercise*, 23(3), 360–3. [An investigation of the contributing factors to acceleration of the tibia].

De Lange, A., Huiskes, R. & Kauer, J.M. (1990). Effects of data smoothing on the reconstruction of helical axis parameters in human joint kinematics. *Journal of Biomechanical Engineering*, 112(2), 107–13. [This study contributed to the methodological foundation of the finite helical axis].

Lee, V.S., Solomonidis, S.E. & Spence, W.D. (1997). Stump-socket interface pressure as an aid to socket design in prostheses for trans-femoral amputees--a preliminary study. Proceedings of the Institution of Mechanical Engineers. Part H, *Journal of Engineering in Medicine*, 211(2), 167–80. [This study used knowledge of pressure distributions to inform prosthesis design].

Light, L.H., McLellan, G.E. & Klenerman, L. (1980). Skeletal transients on heel strike in normal walking with different footwear. *Journal of Biomechanics*, 13(6), 477–80. [An assessment of the effects of footwear on impact forces].

Lindström, L., Kadefors, R. & Petersén, I. (1977). An electromyographic index for localized muscle fatigue. *Journal of Applied Physiology: Respiratory, Environmental and Exercise physiology*, 43(4), 750–4. [An investigation of neuromuscular adaptations to fatigue].

Liu, Z.J. & Herring, S.W. (2000). Bone surface strains and internal bony pressures at the jaw joint of the miniature pig during masticatory muscle contraction. *Archives of Oral Biology*, 45(2), 95–112. [A study of jaw pressure profiles].

Loeb, G.E. & Gans, C. (1986). *Electromyography for Experimentalists*, Chicago, IL.: The University of Chicago Press. [A detailed review and guide of the methodologies for electromyography in the research application]

Loève, M. (1977). *Probability Theory* I (v. 1), Springer. [A learning resource for mathematics on the topic of probability theory]

Mak, A.F., Zhang, M. & Boone, D.A. (2001). State-of-the-art research in lower-limb prosthetic biomechanics-socket interface: a review. *Journal of Rehabilitation Research and Development*, 38(2), 161–74. [A review paper on the measurement of pressure distributions in lower limb prostheses].

Mallat, S.G. (1998). *A Wavelet Tour Of Signal Processing*, Toronto: Academic Press. [A book covering the major concepts and techniques employed in wavelet analysis]

Maness, W.L., Benjamin, M., Podoloff, R., Bobick, A. & Golden, R.F. (1987). Computerized occlusal analysis: a new technology. *Quintessence International* (Berlin, Germany : 1985), 18(4), 287–92. [Measuring pressure distributions using conductive devices].

McLean, S.G., Huang, X., Su, A. & Van Den Bogert, A.J. (2004). Sagittal plane biomechanics cannot injure the ACL during sidestep cutting. *Clinical Biomechanics* (Bristol, Avon), 19(8), 828–38. [An assessment of the potential interactions between movement mechanics and injury].

McMahon, T.A. & Greene, P.R. (1979). The influence of track compliance on running. *Journal of Biomechanics*, 12(12), 893–904. [A study of the effects of sports surface on running performance].

Merletti, R. & Lo Conte, L.R. (1997). Surface EMG signal processing during isometric contractions. *Journal of Electromyography and Kinesiology*, 7(4), 241–250. [A detailed investigation of the neuromuscular characteristics of isometric muscle contractions].

Merlo, E., Pozzo, M., Antonutto, G., di Prampero, P.E., Merletti, R. & Farina, D. (2005). Time-frequency analysis and estimation of muscle fiber conduction velocity from surface EMG signals during explosive dynamic contractions. *Journal of Neuroscience Methods*, 142(2), 267–74. [A detailed description of changes in muscle activation characteristics in maximal dynamic contractions].

Milgrom, C., Finestone, A., Levi, Y., Simkin, A., Ekenman, I., Mendelson, S., Millgram, M., Nyska, M., Benjuya, N. & Burr, D. (2000). Do high impact exercises produce higher tibial strains than running? *British Journal of Sports Medicine*, 34(3), 195–9. [An investigation of the task-dependence of impact forces].

Mitchelson, D.L. (1988). Automated Three-dimensional Movement Analysis Using the CODA-3 System. *Biomedizinische Technik*, 33(7-8), 179–182. [A motion analysis technology based on active markers rather than passive reflective markers].

Morlock, M. & Nigg, B.M. (1991). Theoretical considerations and practical results on the influence of the representation of the foot for the estimation of internal forces with models. *Clinical Biomechanics*, 6(1), 3–13. [This work contributed to the development of more appropriate estimations of the internal forces in the multi-articulate foot].

Neptune, R.R., Kautz, S. a & Zajac, F.E. (2001). Contributions of the individual ankle plantar flexors to support, forward progression and swing initiation during walking. *Journal of Biomechanics*, 34(11), 1387–98. [This study identified the contributions of gastrocnemius and soleus muscles to different stages of limb support and propulsion].

Neptune, R.R., Wright, I.C. & van den Bogert, A.J. (2000). The influence of orthotic devices and vastus medialis strength and timing on patellofemoral loads during running. *Clinical Biomechanics* (Bristol, Avon), 15(8), 611–8. [An investigation of strategies for reducing patellofemoral pain].

Nicol, K. & Hennig, E.M. (1976). Time Dependent Method for Measuring Force Distribution Using a Flexible Mat as a Capacitor. In P. V Komi, ed. *Biomechanics* V-B. Baltimore: University Park Press, pp. 433–440. [A methodological study of force distribution measurement].

Nigg, B.M. & Anton, M. (1995). Energy aspects for elastic and viscous shoe soles and playing surfaces. *Medicine and Science in Sports and Exercise*, 27(1), 92–7. [A discussion of the interactions between footwear and sports surface].

Nigg, B.M. & Denoth, J. (1980). Belastung des menschlichen Bewegungsapparates aus der Sicht der Biomechanik. In B. M. Nigg & J. Denoth, eds. *Sportbelaege*. Zurich: Juris Druck und Verlag, pp. 31–78. [The biomechanical requirements of sports surfaces].

Nigg, B.M. & Herzog, W. (2007). *Biomechanics of the Musculo-skeletal System*, Wiley. [A comprehensive discussion of the biomechanics of the musculoskeletal system]

Nigg, B.M. & Liu, W. (1999). The effect of muscle stiffness and damping on simulated impact force peaks during running. *Journal of Biomechanics*. 32(8), 849–856. [A model of impact forces in heel-toe running].

Nigg, B.M. & Wakeling, J.M. (2001). Impact forces and muscle tuning: a new paradigm. *Exercise and Sport Sciences Reviews*, 29(1), 37–41. [A review of the supporting evidence for muscle tuning].

Nigg, B.M. (2010). *Biomechanics of Sport Shoes*, Calgary, AB.: University of Calgary Press. [A comprehensive discussion of shoe biomechanics research]

Nigg, B.M. (1978). Die Belastung des menschlichen Bewegungsapparates aus der Sicht des Biomechanikers. In *Biomechanische Aspekte zu Sportplatzbelaegen*. Zurich: Juris Druck und Verlag, pp. 11–17. [The biomechanical requirements of sports surfaces].

Nigg, B.M. (1997). Impact forces in running. *Current Opinion in Orthopedics*, 8(6), 43–47. [A review of impact forces in running].

Nigg, B.M., Luethi, S., Denoth, J. & Stacoff, A. (1983). Methodological aspects of sport shoe and sport surface analysis. In H. Matsui & K. Kobayashi, eds. *Biomechanics* VIII-B. Champaign, Illinois: Human Kinetic Publishers, pp. 1041–1052. [A review of the methods for studying the foot / ground interactions].

Nigg, B.M., Bahlsen, H.A., Luethi, S.M. & Stokes, S. (1987). The influence of running velocity and midsole hardness on external impact forces in heel-toe running. *Journal of Biomechanics*, 20(10), 951–9. [A study of the impact forces in running].

Norman, R.W., Bishop, P.J., Pierrynowski, M.R. & Pezzack, J.C. (1979). Aircrew helmet protection against potential cerebral concussion in low-magnitude impacts. *Aviation, Space, and Environmental Medicine*, 50(6), 553–61. [An investigation of impact forces].

Pandy, M.G., Anderson, F.C. & Hull, D.G. (1992). A parameter optimization approach for the optimal control of large-scale musculoskeletal systems. *Journal of Biomechanical Engineering*, 114(4), 450–60. [A modeling approach for solving optimal control problems].

Payne, C.B. (2007). Forces, motion and outcomes with foot orthoses and running shoes. In Proceedings of the 8th Footwear Biomechanics Symposium. Taipei, Taiwan. [A summary of the lack of evidence for foot position and injury in running].

Pedotti, A., Krishnan, V.V. & Stark, L. (1978). Optimization of muscle-force sequencing in human locomotion. *Mathematical Biosciences*, 38(1-2), 57–76. [An example of the consequences of indirect versus direct model comparisons].

Petrofsky, J.S., Glaser, R.M., Phillips, C.A., Lind, A.R. & Williams, C. (1982). Evaluation of amplitude and frequency components of the surface EMG as an index of muscle fatigue. *Ergonomics*, 25(3), 213–23. [An investigation of the neuromuscular responses to fatigue].

Podoloff, R.M. & Benjamin, M. (1989). A Tactile Sensor for Analyzing Dental Occlusion. *Sensors*, 6, 41–47. [An application example for pressure sensing systems].

Polliack, A.A., Sieh, R.C., Craig, D.D., Landsberger, S., McNeil, D.R. & Ayyappa, E. (2000). Scientific validation of two commercial pressure sensor systems for prosthetic socket fit. *Prosthetics and Orthotics International*, 24(1), 63–73. [A technical study to validate pressure sensing systems].

Di Prampero, P.E. (1986). The energy cost of human locomotion on land and in water. *International Journal of Sports Medicine*, 7(2), 55–72. [An analysis of the energy costs of human locomotion].

Press, W.H., Teukolsky, S.A.,Vetterling, W.T. & Flannery, B.P. (1996). *Numerical Recipes in Fortran 90: The Art of Parallel Scientific Computing*, Cambridge University Press. [A comprehensive reference book on scientific computing]

Quesada, P., Rash, G. & Jarboe, N. (1997). Assessment of pedar and F-Scan revisited. *Clinical Biomechanics* (Bristol, Avon), 12(3), p.S15. [This research identified that capacitive sensing technologies are generally more accurate than resistive sensing systems].

Quesada, P.M. & Rash, G.S. (2000). Quantitative assessment of simultaneous capacitive and resistive plantar pressure measurements during walking. *Foot & Ankle International*. / American Orthopaedic Foot and Ankle Society [and] Swiss Foot and Ankle Society, 21(11), 928–34. [This research identified that capacitive sensing technologies are generally more accurate than resistive sensing systems].

Roth, R. (1989). On Constructing Free Body Diagrams. *International Journal of Applied Engineering*, 5(5), 565–570. [A summary of the rules and recommendations for rigid body analysis].

Sanders, J.E., Bell, D.M., Okumura, R.M. & Dralle, A.J. (1998). Effects of alignment changes on stance phase pressures and shear stresses on transtibial amputees: measurements from 13 transducer sites. *IEEE Transactions on Rehabilitation Engineering*, 6(1), 21–31. [An assessment of pressure distributions and shear stress in lower limb amputees].

Sanderson, D.J., Hennig, E.M. & Black, A.H. (2000). The influence of cadence and power output on force application and in-shoe pressure distribution during cycling by competitive and recreational cyclists. *Journal of Sports Sciences*, 18(3), 173–81. [This study quantified the effects of altered gait mechanics on pressure distributions].

Schwartz, R.P. & Heath, A.L. (1937). Some factors which influence the balance of the foot in walking The Stance Phase of Gait. *The Journal of Bone & Joint Surgery*, 19(2), 431–442. [An early investigation of dynamic walking balance].

Shem, K.L., Breakey, J.W. & Werner, P.C. (1998). Pressures at the Residual Limb-Socket Interface in Transtibial Amputees with Thigh Lacer-Slide Joints. *Journal of Prosthetics and Orthotics*, 10(3), 51–55. [An assessment of pressure distributions in lower limb amputees].

Shereff, M.J., Bregman, A.M. & Kummer, F.J. (1985). The effect of immobilization devices on the load distribution under the foot. *Clinical Orthopaedics and Related Research*, (192), 260–7. [This study assessed alterations in foot pressure due to modification of gait mechanics].

Shorten, H.R. & Mientijes, M. (2003). The effects of shoe cushioning on impact force during running. In 6th Symposium On Footwear Biomechanics. Otago, N.Z.: University of Otago. [An investigation of impact forces in running].

Shorten, H.R., Valiant, G.A. & Cooper, L.B. (1986). Frequency analysis of the effects of shoe cushioning on dynamic shock in running. *Medicine and Science in Sports and Exercise*, 18(2), S80. [An investigation of impact forces in running].

Soames, R.W. (1985). Foot pressure patterns during gait. *Journal of Biomedical Engineering*, 7(2), 120–6. [An investigation of foot pressure profiles].

Söderkvist, I. & Wedin, P.-Å. (1993). Determining the movements of the skeleton using well-configured markers. *Journal of Biomechanics*, 26(12), 1473–1477. [An application of a least-squares method for determining segment positions and orientations].

Van Soest, A.J., Schwab, A.L., Bobbert, M.F. & van Ingen Schenau, G.J. (1993). The influence of the biarticularity of the gastrocnemius muscle on vertical-jumping achievement. *Journal of Biomechanics*, 26(1), 1–8. [This study investigated the consequences of muscles spanning two joints for the transfer of energy].

Stefanyshyn, D.J. & Nigg, B.M. (1998). Contribution of the lower extremity joints to mechanical energy in running vertical jumps and running long jumps. *Journal of Sports Sciences*, 16(2), 177–86. [An analysis of the task-specific contributions of the lower limbs to the utilization of mechanical energy].

Stefanyshyn, D.J. & Nigg, B.M. (1998). Dynamic angular stiffness of the ankle joint during running and sprinting. *Journal of Applied Biomechanics*. 14(3), 292–299. [A detailed investigation of the task-specific stiffness of the ankle joint].

Stefanyshyn, D.J. & Nigg, B.M. (1997). Mechanical energy contribution of the metatarsophalangeal joint to running and sprinting. *Journal of Biomechanics*, 30(11-12), pp.1081–1085. [This investigation identified sources of energy loss which when minimized improve performance].

Stegeman, D.F. & Linssen, W.H. (1992). Muscle fiber action potential changes and surface EMG: A simulation study. *Journal of Electromyography and Kinesiology*, 2(3), 130–40. [A simulation study of the characteristics of the action potential].

Stegeman, D.F., Blok, J.H., Hermens, H.J. & Roeleveld, K. (2000). Surface EMG models: properties and applications. *Journal of Electromyography and Kinesiology,*, 10(5), 313–26. [A review of the state of neuromuscular modeling].

Sterzing, T.F. & Hennig, E.M. (1999). Measurement of Plantar Pressures, Rearfoot Motion and Tibial Shock During Running 10 km on a 400 m Track. In Proceedings Of Fourth Symposium On Footwear Biomechanics. pp. 88–89. [A detailed quantification of the biomechanics of the foot and ankle in long distance running].

Thorstensson, A., Karlsson, J., Viitasalo, J.H., Luhtanen, P. & Komi, P.V. (1976). Effect of strength training on EMG of human skeletal muscle. *Acta Physiologica Scandinavia*, 98(2), 232–236. [An investigation of neuromuscular adaptations with strength training].

Von Tscharner, V. (2000). Intensity analysis in time-frequency space of surface myoelectric signals by wavelets of specified resolution. *Journal of Electromyography and Kinesiology*, 10(6), 433–445. [This paper provides a detailed description of the wavelet transformation approach developed for the assessment of EMG data in humans].

Urry, S. (1999). Plantar pressure-measurement sensors. *Measurement Science and Technology*, 10(1), R16–R32. [A description of a measuring apparatus for pressure distributions].

Veldpaus, F.E., Woltring, H.J. & Dortmans, L.J.M.G. (1988). A least-squares algorithm for the equiform transformation from spatial marker co-ordinates. *Journal of Biomechanics*, 21(1), 45–54. [This paper explores the methodologies of the finite helical axis].

Voloshin, A. & Wosk, J. (1982). An in vivo study of low back pain and shock absorption in the human locomotor system. *Journal of Biomechanics*, 15(1), 21–7. [An investigation working toward an understanding of the human movement mechanics and joint pathology].

Voloshin, A. & Wosk, J. (1981). Influence of artificial shock absorbers on human gait. *Clinical Orthopaedics and Related Research*, (160), 52–6. [A study investigating the effects of external mechanical devices on movement mechanics].

Wakeling, J.M., Liphardt, A.-M. & Nigg, B.M. (2003). Muscle activity reduces soft-tissue resonance at heel-strike during walking. *Journal of Biomechanics*, 36(12), 1761–1769. [A study exploring the concept of muscle tuning].

Wakeling, J.M., Nigg, B.M. & Rozitis, A.I. (2002). Muscle activity damps the soft tissue resonance that occurs in response to pulsed and continuous vibrations. *Journal of Applied Physiology*, 93(3), 1093–1103. [A study exploring the concept of muscle tuning].

Weightman, B. (1976). The Stress in Total Hip Prosthesis Femoral Stems: A Comparative Experimental Study. *Engineering in Medicine*, 2, 138–147. [An investigation of the mechanical requirements on hip prostheses].

Williams, K.R. (1985). The relationship between mechanical and physiological energy estimates. *Medicine and Science in Sports and Exercise*, 17(3), 317–25. [This paper combines the concepts of mechanical and metabolic energy to investigate their relationship].

Winter, D.A., Fuglevand, A.J. & Archer, S.E. (1994). Crosstalk in surface electromyography: Theoretical and practical estimates. *Journal of Electromyography and Kinesiology* 4(1), 15–26. [In this paper the concepts and implications of electrical crosstalk between muscles is reviewed].

Winter, D.A. (1979). A new definition of mechanical work done in human movement. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, 46(1), 79–83. [This paper addresses the fundamentals of mechanical energy in humans].

Winter, D.A. (1978). Calculation and interpretation of mechanical energy of movement. *Exercise and Sport Sciences Reviews*, 6, pp.183–201. [This is a key paper in the development of methodologies of mechanical energy].

De Wit, B., De Clercq, D. & Lenoir, M. (1995). The effect of varying midsole hardness on impact forces and foot motion during foot contact in running. *Journal of Applied Biomechanics*, 11(4), 395–406. [An analysis of footwear properties on impact force attenuation].

Woltring, H.J. & Huiskes, R. (1985). A Statistically Motivated Approach to Instantaneous Helical Axis Estimation from Noisy, Sampled Landmark Coordinates. In D. A. Winter et al., eds. Biomechanics IX-B. Champaign, IL: *Human Kinetics*, pp. 274–279. [A detailed description of the FHA approach to describe joint motion].

Woltring, H.J. & Marsolais, E.B. (1980). Optoelectric (Selspot) Gait Measurement in Two- and Three-dimensional Space: A Preliminary Report. Bulletin of Prosthetics Research, 17(2), 46–52. [A methodological summary of the measurement of movement kinematics].

Woltring, H.J. (1994). 3-D attitude representation of human joints: a standardization proposal. *Journal of Biomechanics*, 27(12), 1399–414. [This paper reviews and formulates standards for the description of movement kinematics].

Woltring, H.J. (1991). Representation and calculation of 3-D joint movement. *Human Movement Science*, 10(5), 603–616. [An important review of the computation of inverse dynamics].

Wright, I.C., Neptune, R.R., van den Bogert, A.J. & Nigg, B.M. (2000). The influence of foot positioning on ankle sprains. *Journal of Biomechanics*, 33(5), 513–9. [This paper aimed to identify the role of ankle kinematics in the development of sports injury].

Zadpoor, A.A., Nikooyan, A.A. & Arshi, A.R. (2007). A model-based parametric study of impact force during running. *Journal of Biomechanics*, 40(9), 2012–21. [This paper describes a model that describes the source of running impact forces].

Zadpoor, A.A. & Nikooyan, A.A. (2006). A mechanical model to determine the influence of masses and mass distribution on the impact force during running--a discussion. *Journal of Biomechanics*, 39(2), 388–9. [A review of the effects of body mass properties on impact forces].

Zadpoor, A.A. & Nikooyan, A.A. (2010). Modeling muscle activity to study the effects of footwear on the impact forces and vibrations of the human body during running. *Journal of Biomechanics*, 43(2), 186–93. [An investigation of the role of the musculature in regulating impact forces].

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 Lowa 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.