Biomechanics of Lower Limb Prosthetics
Mark R. Pitkin

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Foreword from a Clinical Biomechanist, Applied Physiologist and Prosthetist teaching graduate students in Prosthetics & Orthotics.

While there are many books on Biomechanics, arguably the quintessential science of limb prosthetics, none addresses the fundamental principles in sufficient detail and depth to be practically useful to the prosthetist, rehabilitation specialist or researcher. Dr. Pitkin’s monograph is an exemplary collection of theoretical principles from his research and others, presented in its clinical and applied biomechanics form. The textbook provides an excellent overview of the many facets of lower limb prosthetic design and engineering for the ardent clinician researcher and student.

The book delves into many of the basic concepts that are required knowledge for the clinician and the scientist to have as the foundation for their work. Dr. Pitkin has an eloquent manner in which he reflects on the history and literature to tell the storied evolution of prosthetic design. He takes the reader on a journey to consider his theories, which have substantive foundations to contemplate. By the end of chapter one, we have the basic history and an appreciation for the rationale behind the “rolling joint ankle” with evidence to support his theoretical views.

For a subject as potentially challenging as Biomechanics, this book easy to read. Of course our bias is the love and passion for the field, which is similarly felt in Pitkin’s writing. We are sure many of our prosthetic colleagues may be equally refreshed as they challenge the rationale that supports their clinical treatment philosophies. The mathematical modeling and design parameters of “rolling joint” theory provide an appreciation for the design elements of componentry that are incorporated in a prosthesis. One will surely look at an ankle, foot, and knee mechanisms with much greater scrutiny after reflecting on this book.

Another invaluable feature of this work is the numerous techniques and methods presented throughout the text to evaluate and measure the performance of a prosthesis with its user or its individual components. The measurement tools are described in enough detail that even the non-biomechanist can appreciate their value and their relative importance in defining functional outcomes. Dr. Pitkin presents a solid case on how reduced joint moments may influence the forces acting on the residuum. With this general theme throughout the book he offers a perspective in the final chapter that
delineates the advantages and challenges of direct skeletal attachment versus the conventional “socket-residuum” type prosthetic interface.

For the biomechanist, clinician and student of prosthetics, this book is surely a necessity in one's library, not only as a reference, but also as the definitive perspective on fundamental biomechanical principles of lower limb prosthetic design. For us who teach graduate students in Prosthetic and Orthotics it is very important to select educational materials of the highest quality and relevance to the profession. This explains our interest in the book of Dr. Pitkin which despite its small size illuminates many undeveloped areas in biomechanics of locomotion, links biomechanics, physiology, and engineering in a united framework, and provides clear guidance to the students on how to design lower limb prostheses.

With the rolling joint foot, ankle, and knee prostheses as examples, the book gives a step-by-step description of the classical design process with relevant mathematical modeling, mechanical testing, and biomechanical evaluations in amputees wearing these devices. What is important for the educational purposes is that the general outline of the prosthetic design presented in the book can be applied to the construction of any new limb prosthesis. The described methodology of gait analysis and pressure measurements allows one to appreciate importance of objective comparative evaluations of different types of prostheses in terms of their impact on amputee’s performance and comfort/discomfort. The abovementioned features of the book make it, in our opinion, a useful tool in research and teaching of the future professionals in the field of Prosthetics.

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Professor Pitkin in his monograph summarizes the results of many years of work in the field of mathematical and structural modeling as a foundation for design and manufacturing contemporary lower limb prostheses. I would like to say a few words about the author, as I have known him for more than 30 years. Dr. Pitkin began his research career at the Albrecht Institute for Prosthetic Research in St. Petersburg (Russia), where he completed several stages of professional development to eventually become the Director of the Laboratory of Foot Biomechanics. Since 1990, Dr. Pitkin has worked in the US, where he founded the Center for Human Performance at New England Sinai Hospital, Stoughton, MA, and holds the position of Research Professor at Tufts University School of Medicine, Boston, MA.

Professor Pitkin has gained an international reputation in biomechanics of normal and prosthetic locomotion, and was able to introduce into practice a number of his ideas and inventions, which is not so often the case in academia. He runs the International Institute for Prosthetic Rehabilitation of Landmine Survivors, and the research company Poly-Orth International. He manages to touch all stages of development from the initial hypothesis to the final product, and he shares this experience with the readers of this book.

A central topic of this monograph is the scientific story about the biomechanical roots of an idea that is as simple as it is brilliant: That the prosthetic joint should mimic relative rolling seen in joints of sound people (Chap. 1). Multilayer studies followed, and the reader will be able to follow the flow of ideas and data analysis resulting in a new prosthesis (Chap. 2–5). A novel approach to anthropomorphicity of lower limb prostheses is connected to the author’s theory of ballistic synergy in normal gait and gait with prosthesis (Chap. 3). It has been demonstrated that focused synthesis of prosthetic joints (Chap. 4) could decrease excessive forces on amputee’s residuum bringing the prosthetic synergy close to the normal one (Chap. 5).

The monograph also includes the author’s original concept of antiresonance, being formulated as Principle of spectral reciprocity in biomechanics of locomotion (Chap. 6). As Dr. Pitkin’s other ideas, this one will seem so obvious, but only after you become involved in the author’s circle of reasoning and proofs. The last part of the book (Chap. 7) is devoted to the requirements of lower limb prostheses if their attachment is going to be direct in contrast with the traditional residuum-socket technology. We can see here that Dr. Pitkin’s Rolling Joint technology, which aimed at reducing forces that the prosthetic socket exerts...
on the residuum, can be applied to the technology of direct skeletal attachment to prolong the safe bond of the implanted connector with the amputee’s residuum.

I am confident that this monograph by Professor Pitkin will be an important source of ideas and methodology in biomechanics and prosthetics, especially for young devoted professionals.

President of the Russian
Guild of Prosthetists-Orthopedists

Professor Anatoly Keyer, MD, Ph.D.
Public attention to people who need prostheses and to prostheses themselves always grows during times of war and culminates immediately after the war ends. One obvious reason is the sharp rise in the number of amputees. The other reason is the temporary release and availability of technical and intellectual resources, previously devoted to the development of military technologies. The military researchers and engineers turn to the prosthetists, physical therapists, and medical doctors, and say to them approximately the following: “Tell us what to do and we will make it.” The prosthetists, physical therapists, and medical doctors usually trust the military researchers and engineers, and begin speaking. Since they have too many things to tell about, and since the military researchers and engineers are soon called upon for preparations for newer wars, the dialogue ends quite not long after it begins.

Everyone returns to their duty, and the prosthetists, physical therapists, and medical doctors remain with the feeling that the opportunity for fruitful cooperation came when they were not sufficiently prepared. If their goals and objectives were formulated with greater clarity, they feel something exciting would have been achieved.

As a graduate in mechanics from St. Petersburg (Russia) University, I witnessed and was a participant of several such cycles of temporary mergers of high tech and prosthetics, having sat on both sides of the aisle, both in Russia and in the US. Therefore, I was either in a position to answer the question “what is needed,” or in the position to ask this question to others or to myself. This monograph is a result of my several approximations in an attempt to answer these questions.

Boston, MA

Mark R. Pitkin
I am grateful to my wife for inspiration and to my son for help in preparing the original manuscript and for revising it for the current English edition. I am indebted to my colleagues in Russia and in the United States for their friendship, professional collaboration and conversations that clarified my thinking on this and other matters. I am particularly grateful to Scientific Editor, Professor Anatoly Keyer, President of the Russian Guild of Prosthetists-Orthopedists, and to Scientific Reviewer, Professor Eugene Popechitelev at LETI University for their thoughtful and creative comments. I am grateful to the Tekscan Technologies, Boston, MA, and Vicon, Centennial, CO, for letting me use some of their material in this book. I am pleased to acknowledge the Ohio Willow Wood Co., Mt. Sterling, OH, the United Prosthetics, Boston, MA, and the Albrecht Center for Occupational Expertise, Prosthetics and Rehabilitation, St. Petersburg, Russia, for their contribution to development, manufacturing and testing of the Rolling Joint prostheses. I am especially grateful to Géza Kogler, Boris Prilutsky, and Robert Kistenberg, teaching at the graduate program in Prosthetics and Orthotics at the Georgia Institute of Technology, Atlanta, GA, for being the first readers and reviewers of the English edition of the book and for their professional comments. It was the Human Performance Laboratory at the Calgary University, Canada, the Newman Laboratory for Biomechanics and Human Rehabilitation at the MIT, Cambridge, MA, Department of Physical Medicine and Rehabilitation at Tufts University School of Medicine in Boston, MA, and the New England Sinai Hospital in Stoughton, MA, who provided the conditions under which the studies could take place. Financial support for this work came in part from Michael and Helen Schaffer Foundation and NIH Grants AR43290, HD38143, HD047493, and HD057492.
The lower limb prosthesis is a device that substitutes a part of a limb missing either due to amputation or a congenital defect. The prosthesis is assembled using off-the-shelf components and a custom-made socket for its attachment to the residuum. The residuum assumes the loads for which a sound leg is intended. Skin and other tissues of the residuum take pressures that they were not meant to take. These pressures are new to a wearer of the leg prosthesis, and are among the chief sources of discomfort, pain, and secondary trauma.

There are two approaches to decreasing the unwanted pressures on the residuum. The traditional approach is to develop better technologies for designing and manufacturing the sockets and their attachment to the body. This approach can be called a direct one, since it deals with direct contact between the prosthesis and the human body. However, the envelope of soft tissues around the residuum’s bones is not uniform, and therefore the inner shape of the socket cannot be an exact copy of the residuum. Modifications of the socket dimensions are made manually or with 3D digital CAD/CAM scanning (Lemaire, Bexiga et al. 1999; Jerrell 2006). Further, protective liners made of elastomers are used to redistribute the painful pressures (Coleman, Boone et al. 2004). Socket can even be excluded from the prosthesis’s assembly in a new method of direct skeletal attachment when a metal abutment is implanted into the residuum’s bone (Eriksson and Branemark 1994).

Another approach is to focus on the development of the standardized prosthetic components and on the analysis of their role on the “body–prosthesis” interface. We will call this approach indirect, as it deals with the prosthetic components, which are not in contact with the residuum.

Both direct and indirect approaches use the results of biomechanical studies of normal and prosthetic locomotion. Once biomechanical models are developed for normal locomotion, they can be modified to analyze the contribution of artificial units to compensatory strategies employed by amputees. Further improvements in the units’ design can be evaluated by looking on how they help reduce such compensatory efforts to increase comfort and confidence of a wearer.
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1.1 A Need for Better Functionality of Lower Limb Prostheses

In 2007, there were approximately 1.7 million persons living with limb loss in the U.S.\(^1\)

The main cause of acquired limb loss is poor circulation in the limb owing to arterial disease, with more than half of all the amputations occurring among people with diabetes mellitus. Amputation of a limb may also occur after a traumatic event or for the treatment of bone cancer.

The US Department of Defense reports that as of February 2008, 1,031 individuals underwent amputations, of whom 730 had suffered major limb amputations during Operation Iraqi Freedom in Iraq and Operation Enduring Freedom in Afghanistan (Polly et al. 2004). Of the 1,031 total amputees, 77.5% sustained their injury while in the Army, 18.8% sustained their injury while in the Marines, 2.3% sustained their injury while in the Navy, and 1.4% sustained their injury while in the Air Force (Fischer 2008). Expanded military operations have decreased the mean age of amputation occurrence. The survival rate after severe gunshot and landmine trauma has concurrently increased. The increased survival rate has been made possible by improved immediate medical care on the battle field, fast transporting of the wounded soldiers to definitive care facilities, better instrumentation that allows advanced external fixation of the traumatized limbs, and new surgical materials and techniques. As a consequence, the ratio of “number of amputees vs. number of death casualties” has increased from 7% during WWII and 15% during the Soviet Union’s 1979–1989 war in Afghanistan, to 30% (Nechaev et al. 1995).

If we look at the statistical data published in the 1990s, we can observe the significant growth of the current amputee population. The total number of lower limb amputees in the US was estimated to be 311,000 (Gailey et al. 1994). This number was higher than the total of 300,000 of all the amputees reported in Russia (Nikitin 1996). However, in terms of the percentage of the country’s population, the US had at that period about 0.11% of lower limb amputees when compared with 0.16% in Russia.

The causes of amputation include vascular and circulatory disease (70%), trauma (23%), tumor (4%), and congenital conditions (3%). Of the lower extremity amputations, 40% are trans-femoral, 50% are trans-tibial, and 10% are hip disarticulation (Torres 1994).

\(^1\)National Limb Information Center: http://www.amputee-coalition.org/fact_sheets/limbloss_us.pdf
In the UK, the National Amputee Statistical Database (NASDAB) was established in 1993 with the aim of re-establishing a national amputee database and to implement the collection of data from systems within 44 prosthetic centers (Report 2002b). In 2002, 9 out of 10 lower limb amputations were either trans-tibial (50%) or trans-femoral (40%). More than two-thirds of the lower limb amputees referred in 2001/02 were male (69%). The preponderance of dysvascularity as a cause of amputation is clearly evident (70% of all lower limb amputations): a significant increase from 56% in 1998/1999. Dysvascularity was the most common cause of lower limb amputation amongst all age groups with the exception of those aged under 16, where trauma was more common (Pechman 1991; Bowker and Michael 1992). There was a strong association between age and the cause of amputation. Thirty-nine per cent of the new referrals aged 16–54 had had to undergo amputation as a result of dysvascularity when compared with 74% in those aged over 75 (Glattly 1984).

Problems of stump skin integrity appear immediately after surgery. Sixteen percent of below-knee amputations fail to heal and require reamputation at a higher level (Levy 1983). Even after the patient recovers from the surgery and begins using a definitive prosthesis, skin problems constitute a large percentage of the complications (Thompson 1972). Amputees demonstrate significantly reduced average walking speed (0.85 vs. 1.44 m/s), have longer stance duration (0.85 vs. 0.67 s), and have significantly reduced horizontal ground reaction forces (GRF). These effects are seen on the prosthetic side in the fore direction in the vascular group, and in the fore and aft directions in the trauma group (Skinner and Effeney 1985).

Rejection or not considering prosthetic management can be inferred indirectly by the fact that only 40% of amputees older than 60 years in Glattly’s study (Glattly 1984) were fitted for prosthesis. Therefore, improved and less expensive prosthetic devices would significantly increase the number of positive outcomes in prosthetic rehabilitation for a large portion of the population, including children (Hermodsson et al. 1994; Sapp and Little 1995).

Analysis of the outcome of prosthetic rehabilitation (Nielsen 1991) shows that 50% of trans-tibial amputees in the vascular group and 33% in the trauma group report suffering from stump pain (Helm and Pandian 1994). Pain is a physiological message signaling that stresses are close to the threshold at which tissues could be damaged. Amputees develop compensatory gait strategies to avoid pain and protect the residuum. The most vulnerable part of the residuum is the skin, and problems of residual-limb skin integrity often appear immediately after surgery.

In a national survey of 109 amputees (Hoaglund et al. 1983), 57% reported moderate to severe pain most of the time while wearing the prosthesis. A similarly high incidence of residual pain has been reported in other studies (Nielsen 1991). These results suggest that amputees may expect some level of pain, that they may not fully report these concerns, and that they will continue to wear a prosthesis for as many hours as possible. It was no surprise that the main concerns related to the prosthesis in the study (Gottschalk and Stills 1994) were ranked as comfort – 52, function – 38, cosmesis – 7, and cost – 4%. The studies reveal that more then 50% of all trans-femoral amputees never wear prostheses, or use them no more than 1 h/day, as shown in schematics modified from (Sapp and Little 1995) (Fig. 1.1).

Such statistics are essential for evaluating the functional success of prosthetic rehabilitation and for planning its improvement by developing more functional prostheses. That is