

**A Mechatronic System for Achieving Optimum
Alignment of Lower Limb Prosthesis**

by

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Abstract

Misalignment in the lower limb prosthesis can cause great discomfort in the stump-socket interface and disturbance to gait function. In the long run, it could deteriorate the musculoskeletal system. In practice, the assessment still depends heavily on the verbal feedback of an amputee and experiences of a prosthetist. Moreover it is inconsistent amongst the prosthetists.

Prosthetic alignment involves the adjustment of the prosthetic components relative to the gait quality. Some methods were proposed, including symmetry index, variation in a step-to-step transition, stability within the zone of integrated balance, matching roll-over shape (ROS) to an ideal ROS and etc. It is not clear if the optimum alignment could be achieved. These methods exhibit a few limitations, i.e. limited use of gait variables in a single comparison and non-uniform results when different gait variables are applied. There is a need to provide an objective assessment method that processes high dimensional gait variables and presents them in a simple form. In addition, it could be impractical and expensive clinically to spend excessive time on a patient. An ambulatory gait measurement system could achieve this objective to a certain extent.

This research investigates a potential engineering solution that is able to provide an assistive and objective assessment of the lower limb prosthetic alignment that provides optimal gait quality.

The effort includes a development of a low-cost ambulatory gait measurement system which could be reliably used during indoor and outdoor trials. Human walking trials using the designed ambulatory system are designed and performed to justify the proposed solution. A novel gait analysis method using Principle Component Analysis and Self-Organizing Feature Map is proposed to process high dimensional gait data into a simple plot and a decision guide. The proposed methodology could help to collect sufficient gait data during indoor and outdoor gaits and could provide an objective gait assessment during the application of lower limb prosthetic alignments.

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List of Abbreviations

2D	2 Dimension
3D	3 Dimension
A/D	Analog to Digital
AK	Above Knee
AP	Anterior Posterior
ASYM	Asymmetry
BCOM	Body Centre of Mass
BK	Below Knee
BMB	Bisector of Medial Brim
BMU	Best Matching Unit
CA	Cronbach's Alpha
CAD	Computer Aided Design
CW	Clockwise
CCW	Counter Clockwise
COM	Centre of Mass
COP	Centre of Pressure
CSV	Comma-Separated Values
D/A	Digital to Analog
dof	Degree of Freedom
FO	Foot Off
FS	Foot Strike
FSR	Force Sensitive Resistor
GC	Gait Cycle
GCI	Gait Cycle Index
GRF	Ground Reaction Force
vGRF	Vertical Ground Reaction Force
HC	Heel Contact
HPF	High Pass Filter
HS	Heel Strike
IC	Initial Contact

IMU	Inertial Measurement Unit
ISw	Initial Swing
L.A.S.A.R.	Laser Assisted Static Alignment Reference
LiNo GC	Linear Interpolated Normalized Gait Cycle
LPF	Low Pass Filter
LR	Load Response
KAF	Knee, Ankle and Foot
MEMS	Micro-Electro-Mechanical Systems
MISO	Master In Slave Out
ML	Medial Lateral
MOSI	Master Out Slave In
MSt	Mid Stance
MSw	Mid Swing
PC	Principle Component
PCA	Principle Component Analysis
PCB	Printed Circuit Board
PSw	Pre-Swing
RHR	Right Hand Rule
RMS	Root Mean Square
ROS	Roll Over Shape
RSD	Relative Standard Deviation
SCLK	Serial Clock
RVCG	Rotational Vibratory Coriolis Gyroscope
s	Standard Deviation
SD	Secure Digital
SE	Standard Error
SOFM	Self-Organizing Feature Map
SPI	Serial Peripheral Interface
SS	Slave Select
TF	Transfemoral
TO	Toe Off
TSA	Total Sway Activity
TSt	Terminal Stance
TSw	Terminal Swing

TT	Transtibial
WBI	Weight-bearing Imbalance
ZPLP	Zero Phase Low Pass Filter



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CHAPTER 1

INTRODUCTION

1.1 Background

Misalignment in lower limb prostheses could cause serious skin issues and damages to the musculoskeletal system if not corrected. Undesired pressure distribution in the stump/socket interface [1-7] would result in great discomfort, and continuous mechanical abrasion will eventually cause tissue breakdown, bruise, irritation, stump pain and skin problems. Stump skin damages are serious and should be avoided. Furthermore, heavy and consistent dependency on the sound limb would cause undesired pressure distribution to the rest of musculoskeletal system [8] and hence increase in the prevalence of degenerative changes in the lumbar spines and knee.

Currently, there is no agreement amongst practitioners and researchers regarding the parameters and objective methodologies of gait performance assessment to identify the optimum alignment for lower limb prosthesis. Some researchers believe that symmetry [3, 9] is the key in searching for the optimum alignment. They tried to look for the symmetry between the sound leg and the prosthetic leg. Others [10] believe that the assessment should look into the variation in between steps. Meanwhile, another group of researchers believes in stability and minimum energy expenditure [11-13]. Recently some researchers [14, 15] have proposed that matching roll over shape (ROS) as close as possible to an ideal ROS shape of the foot is the key to a priori alignment. Somehow none of the researchers have claimed confidently that they have found the key of the optimum alignments. Above all, Zahedi [1] proved that the amputees are highly capable to adapt themselves to a broad range of optimum alignments in level walking. He also suggested a set of alignment definitions for both transtibial and transfemoral

prosthesis. Later, Sin [16] re-examined the accepted range and found that a non-level walking test could constraint the acceptable range into a smaller set.

Instrumental gait analysis is crucial for providing a scientific view of walking performance with reported error margins. These instruments provide measurements in temporal, kinematic or kinetic properties of the gait. A gait analysis laboratory may consist of commercial gait measurement instruments such as a vision motion capture system to acquire temporal and kinematic gait data, while using a force plate to measure the ground reaction force within a step. Examples of a vision motion capture system and a force plate are Vicon and Kistler respectively. The commercial motion capture systems provide reliable measurement consistency and accuracy which are reported in their datasheets. In practice, they are expensive and stationary in a confined room.

On the other hand, an ambulatory gait measurement system provides a choice for portable and continuous gait measurements outside a gait laboratory. A number of sensory units that feature light-weight and small in size could be used for direct measurements. A Micro-Electro-Mechanical System (MEMS) type Inertial Measurement Unit (IMU) is light-weight and small in size, relatively cheap, reliable and accurate. An IMU could measure kinematic properties of the limb segments in multiple axes. Commercial MEMS IMUs from Xsens, MEMSense, MicroStrain, MotionNode etc. for example, give a broad range of selections such as types and number of transducers (accelerometer, gyroscope and magnetometer) incorporated, number of degree of freedom (dof) per transducer, signal choices (USB, SPI, I2C, RS232 or analogue voltage) as well as the calibration and analytical software. Off-the-shelf IMUs for gait measurement are rather expensive as compared to their electronic components. An example of MEMS IMU is the integration of ADXL335 (3-axis accelerometer, Analog Devices, Inc.) and IDG500 (2-axis gyroscope, InvenSense, Inc.). However, skilled circuitry development to assemble these ICs is required. The IMU needs to be calibrated before applying it for motion data acquisition.

Controversy on the lower limb alignment might be due to disagreements in gait-alignments assessments. The disagreements could be categorized in two major groups. Firstly the algorithms of assessment and secondly choices of measured gait parameters. Many algorithms are suggested, including symmetry index, variation in a step-to-step transition and ROS as explained above. However limited choices of

gait parameters are suggested to be weighted via these algorithms since these algorithms are mathematically incapable to handle high dimensional data at once. Nowadays, gait data are easily available in high dimensions. It may be an irrational sense just to limit to a number of choices. Since walking is a series of voluntary controlled motions, the gait data should map to a distribution with a centre tendency. The gait data are postulated to form the gait patterns as the results of alignments and other restrictions. Next, the challenge would be to present the multi-dimensional data in a simple form that displays the centre tendency. In practice, a prosthetist spends limited time in monitoring the patient's gait. Short gait monitoring time might possibly result in insufficient observation as the patient leaves the clinic. It is envisaged that an ambulatory system instead of a stationary system would provide a longer observation and collect sufficient gait data.

1.2 Motivation

Some methods were proposed, including symmetry index [5, 9, 16, 17], variation in a step-to-step transition [10, 18], stability within zone of integrated balance [11] and matching roll-over shape (ROS) to an ideal ROS [14, 15] (see arguments of these methods in Chapter 2). These reported methods for lower limb prosthetic alignment assessment still exhibit a few limitations as listed.

1. The first limitation is the limited use of gait variables in a single comparison. For example, a symmetry index would compare the stride speed of the left leg and the right leg. In another example, variations of thigh moments in a step-to-step transition are calculated and plotted to justify the quality of an alignment.
2. The second limitation is the non-uniform sensitivity of the methods when different gait variables are applied. Non uniform results could be produced when different gait variables are applied in the reported methods. This is especially true for the symmetry index and variation in a step-to-step transition. The above methods do not consider compound gait variables at a time. If there are n-sets of gait parameters, there could be n-sets of unequal assessment results. Certain gait parameters are sensitive to the changes of the alignment while certain are not.

3. The third limitation is inadequate observation time during an alignment session. From the prescription point of view, it could be impractical and costly in clinical practices to spend excessive time on a patient. Gait observation during a schedule gait trial could be insufficient to provide adequate gait data for analysis. The amputee would adapt to a new gait pattern over the long run upon any alignment updates. An ambulatory gait measurement system which could continuously collect sufficient amount of gait data out of the clinic could achieve this objective to a certain extent.

It is arguable that the lower limb prosthetic assignment and its assessment must be limited to a pre-scheduled clinical session and must be confined within a certain types of gait variables and must investigate the sensitivity of certain gait variables with regard to the alignment. To date, a typical instrumental gait measurement would easily generate many gait variables. Simple plots and statistical analysis focused on a limited number of gait variables may be insufficient to reveal the 'true' gait quality. It could be a waste of information by discarding part of the gait variables without proper justification. Since human walking involves a high synchronization of falling and supporting of the body controlled by the lower limbs, repeated gait variables measured from predefined body segments could possibly reveal crucial gait patterns due to the alignment. There is a need to provide an objective assessment method for the application of lower limb prosthetic alignment, that acquires sufficient amount of gait data and processes high dimensional gait variables and presents them in a simple form.

1.3 Aims and Objectives

1.3.1 Aims

1. To design a low cost portable mechatronic system that is able to monitor gait in lower limb segments during normal walking.
2. To propose a simple gait analysis solution as an objective assessment during lower limb prosthetic alignments.

1.3.2 Objectives

1. To develop an ambulatory system for gait data collection. The system should be portable and low cost.
2. To calibrate the ambulatory system including the datalogger and the sensors. The efforts should specify the system and provide margin of errors.
3. To collect gait data using the ambulatory system under several walking restrictions.
4. To propose a procedure of gait data processing. The procedure involves multi-stages of signal processing and conditioning.
5. To propose a simple presentation of gait data that could provide essential visual aids and guides during lower limb prosthetic alignments.

1.4 The Scope of this Research

The project could cover many stages of research and development phases before reaching a clinically proven solution. However, at this early stage, this project is intended to provide a potential solution to the problem and is limited into these scopes.

1. To develop a low-cost ambulatory gait measurement system that could be used indoors and outdoors.
2. To propose a novel assessment method that consider a compound set of gait variables
3. To use healthy subjects to validate the proposed solution

1.5 Contributions of this research

As a contribution to the body of knowledge, part of the thesis are published in peer-reviewed conferences. The development of the ambulatory system as reported in Chapter 3 is published in *The 2011 International Conference of Mechanical Engineering, July 6-8, London, UK, 2011*. Different techniques of static calibration of an triaxial accelerometer and the comparison of these techniques as reported in Chapter 4 are published in:

- *The Eighth IASTED International Conference on Biomedical Engineering, February 16 – 18, Innsbruck, Austria, 2011.*

- *The 2011 International Conference of Mechanical Engineering, July 6-8, London, UK, 2011.*

From the same chapter, the dynamic calibration of a gyroscope using a simple pendulous rig and a statistical method is published in *The 14th International Conference on Climbing and Walking Robots and the Support Technologies for Mobile Machines (CLAWAR2011), September 6-8, Paris, France, 2011*. Further works and findings from the research will be published in peer-reviewed journals. The citations of the publications are listed in Appendix D.

Further contributions of this research work can be summarized as:

1. Proposing the development consideration of an ambulatory system. This includes the embedded system design and the recommendation of IMU sensory axes conversion according to the body axes at predefined body landmarks.
2. Revising and comparing several IMU static calibration methods. The comparison reveals the advantages and disadvantages of each method. An innovative procedure using 6/12 known positions and the iterative mathematical solution proves to be useful and easy to apply.
3. Proposing an innovative dynamic calibration for a gyroscope using a pendulous system.
4. Proposing a validation method for IMU dynamic performance using a pendulous system. The IMU actual outputs are compared with the theoretical models formulated from the principle of circular motions.
5. Proposing a novel set of cross-designed experiments to investigate the effect of a crucial alignment factor (ankles) and the walking level to the gait quality.
6. Proposing an innovative procedure to systematically process the collected gait data into a structure of normalized and linear interpolated gait cycles.
7. Proposing a novel gait assessment algorithm that provides a visual aid and a decision guide using PCA and SOFM. The solution is envisaged to serve as an easy-to-use gait assessment tool for the prosthetists during dynamic alignment or more generally, for normal and pathological gait analysis.

1.6 Organization of the Thesis

The thesis is divided into seven chapters. Chapter 2 reviews the problem background of the research. A general knowledge on human walking and biomechanics is reviewed. This includes essential definitions regarding walking and crucial concepts for gait analysis. The review also investigates specially on the issues regarding lower limb prosthetic alignments. These issues include the importance and the need for the alignments, reviews on many alignment methodologies, tools and their arguments. Lastly, contribution of this research to the body of knowledge are mentioned.

Chapter 3 presents the design and development of an ambulatory system which consists of a customized embedded datalogger, five units of inertial measurement units (IMUs) and straps to hold the devices.

Chapter 4 describes the procedures for both static calibration and dynamic calibration of an IMU. The accelerometers are calibrated using several static calibration techniques and these techniques are compared. A pendulous system is recommended for the dynamic calibration. A frequency distribution method is proposed to calibrate the gyroscope. Finally dynamic performances of an IMU are verified by comparing its theoretical models and the actual measurements in the pendulous system.

Chapter 5 reports the procedures of human walking trials and their results. The experiments are cross-designed using two walking restriction factors that influence the gait. The factors are the ankle and the walking level. The experiments received an ethical approval from the Research Support Unit of the University of Leeds and consents from the participants. The procedure for gait feature extraction is demonstrated. It includes multi-stages of signal processing and conditioning techniques, gait events identification, gait features selection and extraction out of processed gait data. The reliability of the ambulatory system (see Chapter 3) is justified using a statistical method called test-retest reliability.

Chapter 6 proposes a potential objective assessment for the lower limb alignments. Correlation and dimensionality are emphasized to be the issues in multi-variants gait data processing. The proposed solution applies Principle Component Analysis (PCA) and Self-Organizing Feature Map (SOFM) to resolve the above issues. The algorithms generates visual aids and guides that map the gait

patterns in low dimensional plots. By means of a 2D or 3D plot, both PCA and trained SOFM are able to show clear clusters of gait performances under different walking restrictions. A trained SOFM could determine the class of a gait pattern in future applications.

Chapter 7 summarizes the work reported in this thesis, highlights the main findings and outlines future works.



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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the background knowledge regarding the study of human locomotion and lower limb prosthetic alignments. In a broader view, the review would give a general understanding about the studies of human locomotion and their relevant discoveries. In specific, the review would provide a deeper understanding regarding the researches in the lower limb prosthetic alignments and their relevant discoveries. Lastly, the contributions of this research to the body of knowledge are mentioned.

The review starts with fundamental concepts and terminologies in the study of human locomotion. They include formal definitions of walking, anatomical geometry, motions in lower limbs in kinematic and kinetic terms. These definitions form the background knowledge necessary for gait analysis. All studies in human locomotion cannot leave without gait data collection with reliable gait measurement instruments. A review of these instruments and their limitations are provided.

Next, a few human walking models are reported. Each model emphasizes on different key variants that determine gait quality. The classical human walking model, the six determinants, has gone through several challenges and is seriously questioned. However, it still describes well about human walking. The model, dynamic walking, utilizes the law of conservation of energy to model the walking actions. Meanwhile, the model, rocker based inverted pendulum, utilizes the geometry of roll-over shape (ROS) to anticipate the virtual leg length. Optimal values of ROS radius and virtual leg length are suggested.

It is a great clinical concern to provide optimal prosthetic alignments. The concerns include both dermatological and musculoskeletal reasons. The alignment must at least provide a certain extent of proper gait function and comfort. Key

REFERENCES

- [1] Zahedi MS, Spence WD, Solomonidis SE, Paul JP. Alignment of lower-limb prostheses. *J Rehabil Res Dev.* 1986;23:2-19.
- [2] Yang L, Solomonidis SE, Paul JP. The influence of limb alignment on the gait of above-knee amputees. *J Biomech.* 1991;24:981-97.
- [3] Isakov E, Mizrahi J, Susak Z, Ona I, Hakim N. Influence of prosthesis alignment on the standing balance of below-knee amputees. *Clin Biomech.* 1994;9:258-62.
- [4] Levy SW. Skin problems of lower extremity amputee. *Artificial Limbs.* 1956;3:20 - 35.
- [5] Chow DHK, Holmes AD, Lee CKL, Sin SW. The effect of prosthesis alignment on the symmetry of gait in subjects with unilateral transtibial amputation. *Prosthet Orthot Int.* 2006;30:114-28.
- [6] Potter BK, Granville RR, Bagg MR, et al. Special Surgical Considerations for the Combat Casualty With Limb Loss In Pasquina PF, Cooper RA (eds.): *Care of the Combat Amputee.* Washington, US, Office of the Surgeon General at TMM Publications, 2009.
- [7] Levy SW. Skin problems in the amputee. In Smith DG, Michael JW, Bowker JH (eds.): *Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles.* 3 ed. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp. 701-10.
- [8] Murnaghan JJ, Bowker JH. Musculoskeletal complications. In Smith DG, Michael JW, Bowker JH (eds.): *Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles.* 3 ed. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp. 683-700.
- [9] Hannah RE, Morrison JB, Chapman AE. Prostheses alignment: effect on gait of persons with below-knee amputations. *Arch Phys Med Rehabil.* 1984;65:159-62.
- [10] Zahedi MS, Spence WD, Solomonidis SE, Paul JP. Repeatability of kinetic and kinematic measurements in gait studies of the lower limb amputee. *Prosthet Orthot Int.* 1987;11:55-64.
- [11] Breakey JW. Theory of Integrated Balance: The Lower Limb Amputee. *Journal of Prosthetics & Orthotics.* 1998;10:42-4.
- [12] Blumentritt S. A new biomechanical method for determination of static prosthetic alignment. *Prosthet Orthot Int.* 1997;21:107-13.
- [13] Blumentritt S, Schmalz T, Jarasch R, Schneider M. Effects of sagittal plane prosthetic alignment on standing trans-tibial amputee knee loads. *Prosthet Orthot Int.* 1999;23:231-8.

- [14] Hansen AH, Childress DS, Knox EH. Prosthetic foot roll-over shapes with implications for alignment of trans-tibial prostheses. *Prosthet Orthot Int.* 2000;24:205-15.
- [15] Hansen AH, Meier MR, Sam M, Childress DS, Edwards ML. Alignment of trans-tibial prostheses based on roll-over shape principles. *Prosthet Orthot Int.* 2003;27:89-99.
- [16] Sin SW, Chow DH, Cheng JC. Significance of non-level walking on transtibial prosthesis fitting with particular reference to the effects of anterior-posterior alignment. *J Rehabil Res Dev.* 2001;38:1-6.
- [17] Fridman A, Ona I, Isakov E. The influence of prosthetic foot alignment on trans-tibial amputee gait. *Prosthet Orthot Int.* 2005;27:17-22.
- [18] Zahedi MS, Spence WD, Solomonidis SE. The influence of alignment on prosthetic gait. In Murdoch G, Donovan RG (eds.): *Amputation Surgery and Lower Limb Prosthetics.* Oxford, Blackwell, 1988, pp. 367-78.
- [19] Inman VT, Ralston HJ, Todd F. Human Locomotion. In Rose J, Gamble JG (eds.): *Human Walking.* 3 ed. Philadelphia, USA, Lippincott Williams & Wilkins, 2006, pp. 1-18.
- [20] Perry J. *Gait analysis : normal and pathological function.* Thorofare, N.J.: SLACK inc 1992.
- [21] Whittle MW. *Gait analysis: an introduction.* 3 ed. Edinburgh: Butterworth-Heinemann 2002.
- [22] Kirtley C. *Clinical Gait Analysis: Theory and Practice.* Edinburgh: Elsevier 2006.
- [23] Ayyappa E. Normal human locomotion, part1: Basic concepts and terminology. *Journal of Prosthetics & Orthotics.* 1997;9:10 - 7.
- [24] Ayyappa E. Normal human locomotion, part2: Motion, ground reaction force and muscle activity. *Journal of Prosthetics & Orthotics.* 1997;9:42 - 57.
- [25] Winter D. *Biomechanics and motor control of human movement.* 3 ed. Hoboken, New Jersey: John Wiley & Sons 2005.
- [26] Rose J, Gamble JG. *Human Walking.* 3 ed. Philadelphia, USA: Lippincott Williams & Wilkins 2006.
- [27] Winter D. *The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological.* 2 ed. Waterloo, Canada: University of Waterloo 1991.
- [28] Winter D. *Biomechanics and motor control of human movement.* 4 ed. Hoboken, New Jersey: John Wiley & Sons 2009.
- [29] Hibbeler RC. *Engineering Mechanics: Statics & Dynamics.* 9 ed. New Jersey: Prentice-Hall, Inc. 2000.
- [30] Mansfield A, Lyons GM. The use of accelerometry to detect heel contact events for use as a sensor in FES assisted walking. *Med Eng Phys.* 2003;25:879-85.
- [31] Lau H, Tong K. The reliability of using accelerometer and gyroscope for gait event identification on persons with dropped foot. *Gait Posture.* 2008;27:248-57.
- [32] Aminian K, Najafi B, BulaBula C, Leyvraz PF, Robert P. Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. *J Biomech.* 2002;35:689 - 99.
- [33] Tong K, Granat MH. A practical gait analysis system using gyroscopes. *Med Eng Phys.* 1999;21:87-94.

- [34] Pappas IPI, Keller T, Mangold S, Popovic MR, Dietz VM, M. A reliable gyroscope-based gait-phase detection sensor embedded in a shoe insole. *Sensors Journal*, IEEE. 2004;4:268-74.
- [35] Kaufman KR, Sutherland DH. Kinematics of Normal Human Walking. In Rose J, Gamble JG (eds.): *Human Walking*. 3 ed. Philadelphia, USA, Lippincott Williams & Wilkins, 2006, pp. 33-52.
- [36] Saunders J, Inman V, Eberhart H. The major determinants in normal and pathological gait. *Journal of Bone & Joint Surgery*. 1953;35:543-58.
- [37] McGeer T. Passive dynamic walking. *International Journal of Robotics Research*. 1990;9:68-82.
- [38] Childress DS, Gard SA. Commentary on the six determinants of gait. In Rose J, Gamble JG (eds.): *Human Walking*. 3 ed. Philadelphia, USA, Lippincott Williams & Wilkins, 2006, pp. 19-21.
- [39] Gard SA, Childress DS. What Determines the Vertical Displacement of the Body During Normal Walking? *Journal of Prosthetics & Orthotics*. 2001;13:64-7.
- [40] Adamczyk PG, Collins SH, Kuo AD. The advantages of a rolling foot in human walking. *Journal of Experimental Biology*. 2006;209:3953 - 63. .
- [41] Hansen AH, Childress DS, Knox EH. Roll-over shapes of human locomotor systems: effects of walking speed *Clin Biomech*. 2004;19:407-14.
- [42] Miff SC, Hansen AH, Childress DS, Gard SA, Meier MR. Roll-over shapes of the able-bodied knee-ankle-foot system during gait initiation, steady-state walking, and gait termination. *Gait Posture*. 2008;27:316-22.
- [43] Hansen AH, Childress DS, Miff SC. Roll-over characteristics of human walking on inclined surfaces. *Human Movement Science*. 2004;23:807-21.
- [44] Kerrigan DC, Croce UD, Marciello M, Riley PO. A refined view of the determinants of gait: Significance of heel rise. *Arch Phys Med Rehabil*. 2000;81:1077-80.
- [45] Kerrigan DC, Riley PO, Lelas JL, Croce UD. Quantification of pelvic rotation as a determinant of gait. *Arch Phys Med Rehabil*. 2001;82:217-20.
- [46] Croce UD, Riley PO, Lelas JL, Kerrigan DC. A refined view of the determinants of gait. *Gait Posture*. 2001;14:79-84.
- [47] Kuo AD. The six determinants of gait and the inverted pendulum analogy: A dynamic walking perspective *Human Movement Science*. 2007;26:617-56
- [48] Donelan JM, Kram R, Kuo AD. Mechanical work for step-to-step transitions is a major determinant of the metabolic cost of human walking. *Journal of Experimental Biology*. 2002;205:3717 - 27.
- [49] Ortega JD, Farley CT. Minimizing center of mass vertical movement increases metabolic cost in walking. *Journal of Applied Physiology*. 2005;99:2099 - 107.
- [50] Gard SA, Childress DS. The effect of pelvic list on the vertical displacement of the trunk during normal walking. *Gait Posture*. 1997;5:233-8.
- [51] Gard SA, Childress DS. The influence of stance phase knee flexion on the vertical displacement of the trunk during normal walking. *American Journal of Physical Medicine & Rehabilitation* 1999;80:26-32.
- [52] Kuo AD, Donelan JM, Ruina A. Energetic consequences of walking like an inverted pendulum: Step-to-step transitions. *Exercise and Sport Sciences Reviews*. 2005;33:88-97.
- [53] Radcliffe CW. Functional Considerations in the Fitting of Above-Knee Prostheses. *Artificial Limbs*. 1955;2:35-60.

- [54] Quigley MJ. Prosthetic Management: Overview, Methods and Materials. In Bowker JH, Michael JW (eds.): Atlas of Limb Prosthetics: Surgical, Prosthetic and Rehabilitation Principles. 2 ed. Rosemont, IL, American Academy of Orthopedic Surgeons, 1992.
- [55] Alignment of Modular Leg Prostheses. Otto Bock HealthCare LP, 2008.
- [56] Berme N, Purdey CR, Solomonidis SE. Measurement of prosthetic alignment. *Prosthet Orthot Int.* 1978;2:73-5.
- [57] Sin SW, Chow DHK, Cheng JCY. A new alignment jig for quantification and prescription of three-dimensional alignment for the patellar-tendon-bearing trans-tibial prosthesis. *Prosthet Orthot Int.* 1999;23:225-30.
- [58] Radcliffe CW. Mechanical aids for alignment of lower-extremity prostheses. *Artificial Limbs.* 1954;1:20 - 8.
- [59] Radcliffe CW. Above-knee prosthetics. THE KNUD JANSEN LECTURE. 1977.
- [60] Geil MD. Variability among Practitioners in Dynamic Observational Alignment of a Transfemoral Prosthesis. *Journal of Prosthetics & Orthotics.* 2002;14:159-64.
- [61] Uellendahl JE. Bilateral lower limb prostheses. In Smith DG, Michael JW, Bowker JH (eds.): Atlas of Amputations and Limb Deficiencies: Surgical, Prosthetic, and Rehabilitation Principles. 3 ed. Rosemont, IL, American Academy of Orthopaedic Surgeons, 2004, pp. 621-31.
- [62] Radcliffe CW. Four-bar linkage prosthetic knee mechanisms: kinematics, alignment and prescription criteria. *Prosthet Orthot Int.* 1994;18:159-73.
- [63] Evans MJ, Evans JH. A new method for the measurement of prosthetic alignment. *Proceedings of the International Conference on Biomedical Engineering, Hong Kong.* 1994:410-1.
- [64] Staros A. Dynamic Alignment of Artificial Legs with the Adjustable Coupling. *Artificial Limbs.* 1963;7:31-42.
- [65] Foort J, Hobson DA. The wedge disc alignment unit. Report of the prosthetics and orthotics research and development unit. Canada, Manitoba Rehabilitation Hospital, 1964.
- [66] Schuch CM. Dynamic Alignment Options for the Flex-Foot(TM). *Journal of Prosthetics & Orthotics.* 1989;1:37-40.
- [67] Kohpler P, Lind L, Lind K, Rennerfeldt G, Kreicbergs A. A new in-built device for one-point stepless prosthetic alignment. *Prosthet Orthot Int.* 1988;12:103-4.
- [68] Winter D. Kinematic and kinetic patterns in human gait: Variability and compensating effects *Human Movement Science.* 1984;3:51-76
- [69] Saleh M. Alignment and gait optimization in lower limb amputees. In Murdoch G, Donovan RG (eds.): *Amputation Surgery and Lower Limb Prosthetics.* Oxford, Blackwell, 1988, pp. 357-66.
- [70] Geil MD, Lay A. Plantar foot pressure responses to changes during dynamic trans-tibial prosthetic alignment in a clinical setting *Prosthet Orthot Int.* 2004;28:105-14.
- [71] Radcliffe CW, Foort J. The Patellar-tendon-bearing below-knee prosthesis. 1961.
- [72] Moe-Nilssen R. Test-retest reliability of trunk accelerometry during standing and walking. *Arch Phys Med Rehabil.* 1998;79:1377-85.
- [73] Moe-Nilssen R, Helbostad JL. Trunk accelerometry as a measure of balance control during quiet standing. *Gait Posture.* 2002;16:60-8.

- [74] Auvinet B, Berrut G, Touzard C, et al. Reference data for normal subjects obtained with an accelerometric device. *Gait Posture*. 2002;16:124-34.
- [75] Luinge diHJ, Veltink PdiPH. Inclination Measurement of Human Movement Using a 3-D Accelerometer With Autocalibration. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*. 2004;12:112-21.
- [76] Henriksen M, Lund H, Moe-Nilssen R, Bliddal H, Danneskiold-Samsøe B. Test-retest reliability of trunk accelerometric gait analysis. *Gait Posture*. 2004;19:288-97.
- [77] Luinge HJ, Veltink PH. Measuring orientation of human body segments using miniature gyroscopes and accelerometers. *Medical & Biological Engineering & Computing*. 2005;43.
- [78] Jasiewicz JM, Allum JHJ, Middleton JW, et al. Gait event detection using linear accelerometers or angular velocity transducers in able-bodied and spinal-cord injured individuals. *Gait Posture*. 2006;24:502-9
- [79] Torrealba RR, Cappelletto J, Fermin-Leon L, Grieco JC, Fernandex-Lopez G. Statistics-based technique for automated detection of gait events from accelerometer signals. *Electronics Letters*. 2010;46:1483-5
- [80] Takeda R, Tadano S, Todoh M, Morikawa M, Nakayasu M, Yoshinari S. Gait analysis using gravitational acceleration measured by wearable sensors. *J Biomech*. 2009;42:223-33.
- [81] González RC, López AM, Rodríguez-Uría J, Álvarez D, Alvarez JC. Real-time gait event detection for normal subjects from lower trunk accelerations. *Gait Posture*. 2010;31:322-5.
- [82] Gouwanda D, Senanayake SMNA. Identifying gait asymmetry using gyroscopes—A cross-correlation and Normalized Symmetry Index approach. *J Biomech*. 2011;44:972-8.
- [83] Rueterbories J, Spaich EG, Larsen B, Andersen OK. Methods for gait event detection and analysis in ambulatory systems. *Med Eng Phys*. 2010;32:545-52.
- [84] Lötters JC, Schippe J, Veltink PH, Olthuis W, Bergveld P. Procedure for in-use calibration of triaxial accelerometers in medical applications. *Sensors and Actuators A: Physical*. 1998;68:221-8.
- [85] Titterton DH, Weston JL. *Strapdown Inertial Navigation Technology*. 2 ed, Institution of Engineering and Technology 2004.
- [86] Grewal MS, Weill LR, Andrews AP. *Global Positioning Systems, Inertial Navigation, and Integration 2ed*. New Jersey: John Wiley & Sons 2007.
- [87] ADXL330. Accelerometers: Small, Low power, 3-axis $\pm 3g$. Analog Device, Inc., 2006.
- [88] ADXL335. Accelerometers: Small, Low power, 3-axis $\pm 3g$. Analog Devices, Inc. , 2009.
- [89] IDG300. Integrated Dual-Axis Gyro. InvenSense, Inc., 2006.
- [90] IDG-500. Integrated Dual-Axis Gyro. InvenSense, Inc., 2008.
- [91] Fisher CJ. AN-1057: Using an Accelerometer for inclination sensing. In *Analog Device I (ed.)*. Rev 0 ed, 2010.
- [92] Rotary Table, 4" H/V. http://littlemachineshop.com/products/product_view.php?ProductID=1927&category=.
- [93] Skog I, Handel P. Calibration of a MEMS Inertial Measurement Unit. XVII IMEKO WORLD CONGRESS, Metrology for a Sustainable Development, September, 17-22, 2006 Rio de Janeiro, Brazil, 2006.

-
- [94] Britting KR. Inertial Navigation Systems Analysis: Wiley-Interscience 1971.
- [95] Strang G. Introduction to Linear Algebra. 4 ed: Wellesley-Cambridge Press 2009.
- [96] Hung JC, Thacher JR, White HV. Calibration of accelerometer triad of an IMU with drifting Z -accelerometer bias. Aerospace and Electronics Conference, 1989 NAECON 1989, Proceedings of the IEEE 1989 National. 1989;1:153 - 8.
- [97] Venkataraman P. Applied Optimization with MATLAB Programming. 2 ed. New Jersey: John Wiley & Sons, Inc. 2009.
- [98] Matlab. ver.7.9.0.529 [R2009b] ed, The Mathworks, 2009.
- [99] Field A. Discovering Statistics Using SPSS. 3 ed. London, UK: Sage Publications Ltd 2009.
- [100] Torrealba RR, Castellano JM, Fernandex-Lopez G, Grieco JC. Characterisation of gait cycle from accelerometer data. Electronics Letters. 2007;43:1066-8.
- [101] Kavanagh JJ, Menz HB. Accelerometry: A technique for quantifying movement patterns during walking. Gait Posture. 2008;28:1-15.
- [102] Manly BFJ. Multivariate statistical methods: a primer. 3 ed. London, UK: Chapman & Hall 2005.
- [103] Kohonen T. Self-Organizing Maps. Heidelberg: Springer 1997.
- [104] Hagan MT, Demuth HB, Beale M. Neural Network Design. Boston: PWS Publishing Company 1996.
- [105] Winter D. Motor patterns in amputee gait: motor adaptations and implications for redesign. Biomedical Engineering, Proceedings of a Special Symposium on Maturing Technologies and Emerging Horizons in. 1988:18-9.

