www.arpnjournals.com

A VISUAL GUIDE FOR LOWER LIMB PROTHETIC ALIGNMENT

Kian Sek Tee[1], Chin Fhong Soon[1], Abbas Dehghani[2], David Moser[3] and Saeed Zahedi[3]
[1]Faculty of Electrical and Electronic Engineering, University Tun Hussein Onn Malaysia, BatuPahat, Johor, Malaysia
[2]School of Mechanical Engineering, University of Leeds, Leeds, United Kingdom
[3]Chas A Blatchford & Sons Ltd, Lister Road, Basingstoke, Hampshire, United Kingdom
E-Mail: tee@uthm.edu.my

ABSTRACT

A novel method to provide an objective visual guide during lower limb prosthetic alignment is proposed. A customized ambulatory device was built to collect kinematic and temporal gait data from 3 subjects walking in four different experiment setups. Multiple gait events within a gait cycle and stride time were derived as feature variables and were pre-processed using Principle Component Analysis (PCA). Distinctive clusters due to different walking setups were noticed in a PCA plot in two dimensions. Dispersion of each clusters and distances amongst each other explains the walking variability and differences under different setups.

Keywords: lower limb prosthetic, alignment, visual aid, PCA.

INTRODUCTION

The alignment (Isakov, Mizrahi, Susak, Ona, and Hakim, 1994; Zahedi, Spence, Solomonidis, and Paul, 1986) of lower limb prosthesis involves mechanical adjustments of joints and links, of which affect the comfort and gait function of an amputee. Improper alignments might cause physical damages to the muscular system and musculoskeletal system if ignored. Undesired pressure distribution in the stump/socket interface would result in great discomfort, and continuous mechanical abrasion will eventually cause tissue breakdown, bruise, irritation, stump pain and skin problems. Stump skin damages (Meulenbelt, Geertzen, Dijkstra, and Jonkman, 2007) are serious and should be avoided. Furthermore, heavy and consistent dependency on the sound limb would cause undesired pressure distribution the rest of musculoskeletal system and hence increase in the prevalence of degenerative changes in the lumbar spines and knee.

A few alignment methods were proposed by researchers. Successful static alignment using load line from the body center using a plumb line (Radcliffe, 1994) and laser light (Blumentritt, 1997; Blumentritt, Schmalz, Jarasch, and Schneider, 1999) were introduced. During dynamic alignments, some believe that symmetry (Hannah, Morrison, and Chapman, 1984) was the key in searching for the optimum alignment. Some believe in stability (Isakov *et al.* 1994) and minimum energy expedition (Schmalz, Blumentritta, and Jaraschb, 2002). Others (Hansen, Childress, and Knox, 2000; Hansen, Meier, Sam, Childress, and Edwards, 2003) believe in alignment by matching roll over shape (ROS) as close as possible to an ideal ROS shape. None of the researchers have claimed confidently that they have found the key for optimum alignments. Furthermore, Zahedi(Zahedi *et al.* 1986) proved that the amputees are highly capable to adapt themselves to a broad range of optimum alignments in level walking. And, he had set a coordinate reference system in order to align the prosthesis for both transtibial and transfemoral prosthesis. Later, Sin (Sin, Chow, and Cheng, 2001) re-examined the accepted range and

proposed a non-level walking trial which could restrain into smaller range.

Instrumental aided alignments suffer from two major challenges, i.e. correlated or even redundant variables and dimensionality. Researchers (Chau, 2001) had attempted many gait variables for analysis, including both kinematics and kinetics and analytical solutions. For examples, angular displacement and rate, temporal, insole center of pressure (COP), ground reaction force (GRF), weight line and load line, joint moments and others. Researchers select subjectively a number of gait variables to look into the quality of gait performance without knowing exactly if variables are correlated or the selected variables supplies sufficient gait information. Correlated variables might cause 'noises' while probing the gait performance while visualization on 2D or 3D plots become impossible with increasing number of variables. This project intends to propose PCA as an analytical method to eliminate correlated variables and to reduce dimensionality while providing aided visualization of gait data in a 2D plot. SOM provides both similar clustering plots in 2D and a decision algorithm to map future variables.

The alignment (Isakov *et al.* 1994; Zahedi *et al.* 1986) of lower limb prosthesis involves mechanical adjustments of joints and links, of which affect the comfort and gait function of an amputee. Improper alignments might cause physical damages to the muscular system and musculoskeletal system if ignored. Undesired pressure distribution in the stump/socket interface would result in great discomfort, and continuous mechanical abrasion will eventually cause tissue breakdown, bruise, irritation, stump pain and skin problems. Stump skin damages (Meulenbelt *et al.* 2007) are serious and should be avoided. Furthermore, heavy and consistent dependency on the sound limb would cause undesired pressure distribution the rest of musculoskeletal system and hence increase in the prevalence of degenerative changes in the lumbar spines and knee.

A few alignment methods were proposed by researchers. Successful static alignment using load line

www.arpnjournals.com

from the body center using a plumb line (Radcliffe, 1994) and laser light (Blumentritt, 1997; Blumentritt *et al.* 1999) were introduced. During dynamic alignments, some believe that symmetry (Hannah *et al.* 1984) was the key in searching for the optimum alignment. Some believe in stability (Isakov *et al.* 1994) and minimum energy expedition (Schmalz *et al.* 2002). Others (Hansen *et al.* 2000; Hansen *et al.* 2003) believe in alignment by matching roll over shape (ROS) as close as possible to an ideal ROS shape. None of the researchers have claimed confidently that they have found the key for optimum alignments. Furthermore, Zahedi(Zahedi *et al.* 1986) proved that the amputees are highly capable to adapt themselves to a broad range of optimum alignments in level walking. And, he had set a coordinate reference system in order to align the prosthesis for both transtibial and transfemoral prosthesis. Later, Sin (Sin *et al.* 2001) re-examined the accepted range and proposed a non-level walking trial which could restrain into smaller range.

Instrumental aided alignments suffer from two major challenges, i.e. correlated or even redundant variables and dimensionality. Researchers (Chau, 2001) had attempted many gait variables for analysis, including both kinematics and kinetics and analytical solutions. For examples, angular displacement and rate, temporal, insole center of pressure (COP), ground reaction force (GRF), weight line and load line, joint moments and others. Researchers select subjectively a number of gait variables to look into the quality of gait performance without knowing exactly if variables are correlated or the selected variables supplies sufficient gait information. Correlated variables might cause 'noises' while probing the gait performance while visualization on 2D or 3D plots become impossible with increasing number of variables. This project intends to propose PCA as an analytical method to eliminate correlated variables and to reduce dimensionality while providing aided visualization of gait data in a 2D plot. SOM provides both similar clustering plots in 2D and a decision algorithm to map future variables.

METHODOLOGY

Ambulatory System and Experiment Setups

An IMU-based ambulatory device as shown in Figure-1 to collect gait data was designed. It consists of a data logger, five units of IMU-5DOF, Velcro straps and a vest to carry the data logger. The data logger (DAQ) was customized using a Mbed NXP LPC1768 microprocessor, sampling at 200Hz. Using 10-Bit A/D Converters with SPI Interface (MCP3008, μchip), 32 analogue inputs were expanded. An IMU is built from a triaxial accelerometer (ADXL330/ADXL335) and a dual-axial gyroscope (IDG300/IDG500), assembled in a compact PCB breakout (SparkFun Inc.). Before use, the IMU were carefully calibrated. The IMUs were strapped onto pre-defined body landmarks, i.e. both lateral shanks and thighs and lastly the sacrum (named as BCOM).

Three healthy subjects had given their consents to participate in the experiments. The subjects were allowed to adapt themselves with the system once the ambulatory system was put on and before commencing a new experiment setup. The experiment received ethical approval from the university research support. Four experiment setups were designed to verify the effect of ankle as the key alignment factor and environment restriction such as different walking levels could result in gait changes. Setup 1 (S1) required the subjects to walk normally on a 6m length flat level; Setup 2 (S2) required the subjects to walk while ankles were locked at 90^0 by wearing a foot orthotic (Motion Walker, www.physiotherapystore.com); Setup 3 (S3) required the subjects to walk normally on a manual treadmill tilted at 5^0; Setup 4 (S4) required the subjects to walk on the manual treadmill tilted at 5^0 while ankles were locked at 90^0 by wearing the foot orthotic. Five to eight trials were recorded for each setup. In between trials, the subjects were allowed to rest for a minute. The subjects were asked to repeat the same experiments in the following week.

Figure-1. Setup of Gait Monitoring System.

Principle Component Analysis

Principle Component Analysis (PCA) is an orthogonal transformation that converts a set of correlated variables $[\vec{X}_1 \vec{X}_2 \cdots \vec{X}_k \cdots \vec{X}_m]$ into another set of uncorrelated variables $[\vec{Z}_1 \vec{Z}_2 \cdots \vec{Z}_l \cdots \vec{Z}_m]$ called principle components (PCs). The principle components are the linear combination of input variables such that

$$Z_l = \beta_{l1}\vec{X}_1 + \beta_{l2}\vec{X}_2 + \cdots + \beta_{lm}\vec{X}_m$$ and

$$\beta_{l1}^2 + \beta_{l2}^2 + \cdots + \beta_{lm}^2 = 1.$$ These principle components are orthogonal to each other. PC1 represents the highest percentage of total variability, followed by PC2 and so on.

Preparation for PCA

Some prerequisite data processing and management are needed before PCA. These include: 1. gait event identification; 2. signals low pass filtering; 3. gait cycle and stride time extraction; 4. feature selections within a GC, extraction and stacking of features and stride time; 5. creating a features matrix per subject from multiple features stacks generated from each experiment setups.

www.arpnjournals.com

Gait event identification and signal low pass filtering

Critical gait events such as Heel-Contact (HC) and Toe-off (TO), can be visually identified from the outputs of the accelerometers and gyroscopes. The magnitudes of the IMU outputs attenuated (Kavanagh andMenz, 2008) as its location approximates proximally. Many researchers (Aminian, Najafi, BulaBula, Leyvraz, and Robert, 2002; Auvinet *et al.* 2002; Jasiewicz *et al.* 2006; Pappas, Keller, Mangold, Popovic, and Dietz, 2004; Rueterbories, Spaich, Larsen, and Andersen, 2010; Tong andGranat, 1999) suggested gait events identification from different axes and locations of body such as gyroscope lateral axis at shanks (Aminian *et al.* 2002; Jasiewicz *et al.* 2006; Pappas *et al.* 2004; Rueterbories *et al.* 2010; Tong andGranat, 1999), accelerometer outputs at shanks (Jasiewicz *et al.* 2006; Rueterbories *et al.* 2010) and at BCOM (Auvinet *et al.* 2002; Rueterbories *et al.* 2010). The authors adapt shanks IMUs as shown in Figure-2to aid in gait event identification especially gyroscope lateral axis at the shank since it is visually clearest of all before filtered. A leg stride is a gait cycle (GC) and is defined as the period between HC to HC. Each leg has its own gait cycle indexes (GCI) based on marked gait events on gyroscope lateral axis. All time-series gait data are filtered using a Zero Phase Low Pass Filter, $f_c = 3Hz$. Using the indexes, filtered gait could be extracted accordingly. For example, using GCI for the right leg, a new array of gait cycle of each axis was generated. Filtered IMU outputs for each legs and BCOM are extracted with the same principle. Time is normalized and using linear interpolation, all normalized GCs are remapped to the same vector length. Eventually, all GCs were stacked. At this stage, stacked GCs are useful in many analytical purposes, such as statistical analysis.
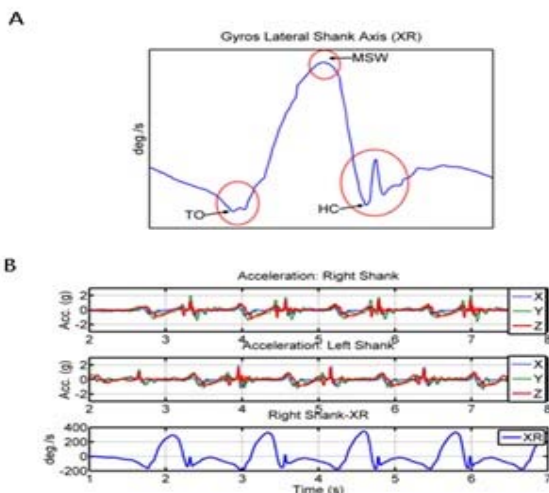
Figure-2. A. Gait events (HC TO MSW) definitions using gyroscope lateral shank axis. B. Gait identification aided by shanks accelerometers.

GC extraction

There are numerous choices of gait features as input variables for PCA, for simplicity reason, only

$[\overrightarrow{HCMSTTOMSW}]$ were selected. MST is defined as the gait period at 0.4 of GC. Besides that, left and right stride times were included into the input variables. There were in total 102 input variables, i.e. 5 IMU x 5 axis x 4 features + 2 Left/Right Stride Time.
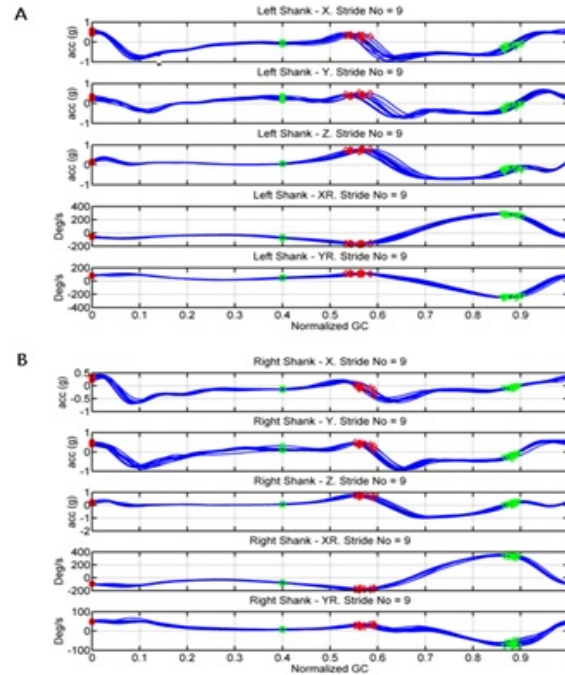

Figure- shows an example of extracted GC stacks marked with selected variables of subject1 during normal level walking in the first week.

All input variables are organized, forming a feature matrix as defined as

$$\begin{bmatrix} \vec{S}_1 \\ \vec{S}_2 \\ \vec{S}_3 \\ \vec{S}_4 \end{bmatrix} \rightarrow \begin{bmatrix} \vec{X}_{11} & \vec{X}_{12} & \cdots & \vec{X}_{1m} \\ \vec{X}_{21} & \vec{X}_{22} & \cdots & \vec{X}_{2m} \\ \vec{X}_{31} & \vec{X}_{32} & \cdots & \vec{X}_{3m} \\ \vec{X}_{41} & \vec{X}_{42} & \cdots & \vec{X}_{4m} \end{bmatrix} \quad (1)$$
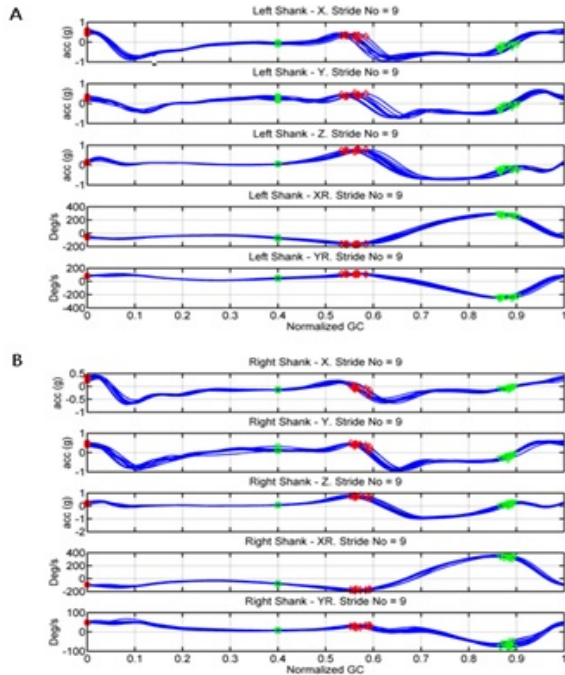
where:

$\vec{S}_1 to \vec{S}_4$ labels of every observation in corresponding experiment setups

$\vec{X}_{tm}$ selected features as input variables

Matrix rows are the observations and are labelled accordingly to the experiment setups. Matrix columns are the input features. Before processed using PCA, all column vectors are standardized.

www.arpnjournals.com

Figure-3. Subject1 Week1: Example of GC Stacks of Left (A) and Right Shanks (B) during Normal Level Walking, Marked With [HC MST TO MSW].

	(HC)	Heel-Contact
★	(MST)	Mid-Stance
□	(TO)	Toe-Off
◇	(MSW)	Mid-Swing
▽		

It is the main interest to plot all observations after processed in PCA in a plot of PC1 versus PC2 to see the distribution of clusters. However, PC1 and PC2 only represent a portion of total variability.

RESULTS AND DISCUSSIONS
It is crucial that the ambulatory gait measuring system is reliable and consistent over time. All IMU axes were checked for their reliability using Test-retest reliability method. Two criteria, i.e. subject and normal walking on flat level, were kept the same except different trials over a week interval. Table-1 shows that Cronbach's Alpha (CA) (mean>0.8, s<0.12) of extracted filtered gait cycles of subject1 were noticed on all IMU units, suggesting the system is reliable and consistent.

Table-1. Example of Cronbach's Alpha of subject1.

IMU No	Loc		X	Y	Z	XR	YR
1	RS	$\bar{x}$	0.977	0.979	0.979	0.993	0.964
		s	0.009	0.015	0.022	0.005	0.024
2	LS	$\bar{x}$	0.779	0.970	0.943	0.981	0.811
		s	0.046	0.010	0.015	0.006	0.024
3	RT	$\bar{x}$	0.934	0.984	0.957	0.985	0.951
		s	0.018	0.009	0.008	0.011	0.022
4	LT	$\bar{x}$	0.919	0.929	0.970	0.992	0.834
		s	0.020	0.018	0.014	0.003	0.026
4	C	$\bar{x}$	0.960	0.970	0.977	0.810	0.934
		s	0.016	0.011	0.011	0.118	0.022

RS = Right Shank, LS = Left Shank, RT = Right Thigh, LT = Left Thigh, C = Body Centre of Mass (BCOM)

$\bar{x}$ = mean, s = standard deviation
[X, Y, Z] = Outputs of accelerometer
[XR, YR] = Outputs gyroscope

The quality of repetitive GC under several restrictions could be visually read from a 2D PCA plot with certain extent of confidence. Figure-4 shows the results of PC1 and PC2 for three subjects over two weeks with an average of 53% of the total variability. Four separated clusters were noticed. The clusters represent the gait performances resulted from different walking restrictions. All subjects exhibit almost repetitive clusters locations and dispersions, i.e. (S1) normal walking on a flat level were clustered on the left side; (S2) walking on flat level with ankle-locked were clustered on the bottom; (S3) walking normally on a 5^0 tilted manual treadmill were clustered on the upper and (S4) walking with ankle-locked on a 5^0 tilted manual treadmill were clustered on the right side. Visually, there are slightly differences in two weeks' plots. S1 and S4 are two extreme setups of all and the distance between each other could be visually seen as the farthest. S3 and S4 appeared to closer to each other as compared to other pairs. S1 and S2 (walking on level) are more stable than S3 and S4 as almost anchored at the same locations and the clusters were rather condensed over two weeks. Dispersion of S3 and S4 (walking on tilted treadmill) appeared to be less condensed over two weeks. Furthermore, two major linear separable groups could be identified. Group of 'ankle-freed' (S1, S3) is located on the upper left side while group of 'ankle-locked' (S, S4) is located on the lower right side. Group of 'level' (S1, S2) is located at the lower left side while group of 'tilted level' (S3, S4) is located at the upper right side. However, groups of (S1, S4) and (S2, S3) are meaningless because they are not linearly separable.
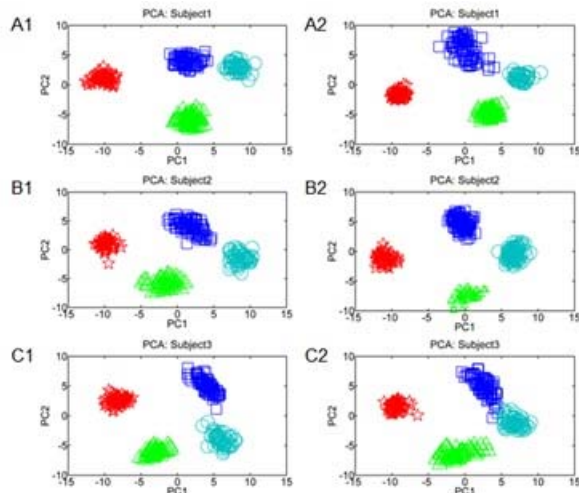
Figure-4. PC1-PC2 plots of all subjects in week1 (A1,B1,C1) and week2 (A2,B2,C2) respectively.

(S1) Walking normally on flat level
(S2) Walking with ankle-locked on flat level
(S3) Walking normally on a 5^0 tilted manual treadmill
(S4) Walking with ankle-locked on a 5^0 tilted manual treadmill

Lower limb prostheses are to provide comfort and function to amputees. After prescription, alignment determines if these objectives are optimized. It is an iterative process that needs great patience and careful observations. The gait is affected by many factors, including the alignments, prosthetic types, and terrace quality, confidence of walking, age, health and etiological causes. Above all, walking is a controlled sequence of falling and supporting of body. This paper has hypothesized that statistically, human gait display a center tendency which is the result of self-adaptation or controlled sequences. These center tendency could be observed subjectively by the prothetists, of which already the clinical practices, or observed objectively through kinematic and kinetic parameters collected from an instrument and analyzed using efficient algorithms.

For the purpose of gait observation after alignment, an instrumental gait analysis should give a facility to multiple terraces and long hour observations. A reliable and portable ambulatory device proposed here did exhibit a high level of reliability (mean Cronsbach's Alpha > 0.8).

It is usual that the gaits are observed in average methods such as average walking speed and cadence or specific terms within a stride or step such as tempo and magnitude of gait events. Multi-variants of kinematic and kinetic parameters have enriched the choices of analysis but at the same time confused the analyst. Two important issues are raised here, i.e. correlation or at worse redundancy and 'curse of dimensionality'. It is likely to be a subjective selection of gait features to represent a study although a statement might possibly explain the reasons.

Meanwhile, complexity arises when the number of features increases. Visualization of features becomes difficult in 3D and is impossible in higher dimensions. Multi-variant analysis like PCA is the simplest method to eliminate correlation amongst features and to reduce dimensionality. A 2D or 3D plots of principle components could provide a visual aid in some extent of confidence. With PCA, it is free to choose a huge variety of features.

While plots of 2D or 3D principle components provide visual guides, a trained SOM provides aids in decision making that defines the category of a collection of same gait features. Although the results showed clearly separated clusters of four different waking restrictions, the authors foresee that in real applications via re-defined walking restrictions, the clusters might be close to each other or even overlapping wholly or partially as viewed in a 2D principle components plot. A computational decision making algorithm will provide a suggestive aids on top of visual guides.

The authors reckon that the method proposed here suffers from a few challenges. The method could be further refined and verified with a number of amputees from groups of amputation level, gender, types of prosthesis and etiological reasons; multiple combinations of alignment parameters; walking trials on different terraces and level. Expertise advices are essential to produce medical evidences of the study.

CONCLUSIONS

A novel method to provide visual guide and computational decision making in optimum alignments of lower limb prosthesis was proposed. Ankle as the key alignment parameter and walking level as alignment parameter restrain were emphasized. Potential studies in possible combinations of amputees' statues, alignment parameters and gait restrictions could help to revise and refine the method.

ACKNOWLEDGEMENTS

REFERENCES

[1] Aminian K., Najafi B., BulaBula C., Leyvraz P. F., and Robert P. 2002. Spatio-temporal parameters of gait measured by an ambulatory system using miniature gyroscopes. Journal of Biomechanics, Vol. 35, No.5, pp. 689 - 699.

[2] Auvinet B., Berrut G., Touzard C., Moutel L., Collet N. and Chaleil D. *et al.* 2002. Reference data for normal subjects obtained with an accelerometric device. Gait & Posture, Vol. 16, No. 2, pp. 124-134.

[3] Blumentritt S. 1997. A new biomechanical method for determination of static prosthetic alignment. Prosthetics and Orthotics International, Vol. 21, No. 2, pp. 107-113.

[4] Blumentritt S., Schmalz T., Jarasch R., and Schneider M. 1999. Effects of sagittal plane prosthetic alignment on standing trans-tibial amputee knee loads. Prosthetics and Orthotics International, Vol. 23, No. 3, pp. 231-238.

[5] Chau T. 2001. A review of analytical techniques for gait data. Part 2: neural network and wavelet methods Gait and Posture, Vol. 13, No. 2, pp. 102 - 120

[6] Hannah R. E., Morrison J. B., and Chapman A. E. 1984. Prostheses alignment: effect on gait of persons with below-knee amputations. Archives of Physical Medicine and Rehabilitation, Vol. 65, No. 4, pp. 159-162.

[7] Hansen A. H., Childress D. S. and Knox E. H. 2000. Prosthetic foot roll-over shapes with implications for alignment of trans-tibial prostheses. Prosthetics and Orthotics International, Vol. 24, No. 3, pp. 205-215.

[8] Hansen A. H., Meier M. R., Sam M., Childress D. S., and Edwards M. L. 2003. Alignment of trans-tibial prostheses based on roll-over shape principles. Prosthetics and Orthotics International, Vol. 27, No. 2, pp. 89-99.

[9] Isakov E., Mizrahi J., Susak Z., Ona I., and Hakim N. 1994. Influence of prosthesis alignment on the standing balance of below-knee amputees. Clinical Biomechanics, Vol. 9, No. 4, pp. 258-262.

[10] Jasiewicz J. M., Allum J. H. J., Middleton J. W., Barriskill A., Condie P., Purcell B. *et al.* 2006. Gait event detection using linear accelerometers or angular velocity transducers in able-bodied and spinal-cord injured individuals. Gait and Posture, Vol. 24, No. 4, pp. 502-509

[11] Kavanagh J. J., and Menz H. B. 2008. Accelerometry: A technique for quantifying movement patterns during walking. Gait and Posture, Vol. 28, 1, pp. 1-15.

[12] Meulenbelt H. E., Geertzen J. H., Dijkstra P. U., and Jonkman M. F. 2007. Skin problems in lower limb amputees: an overview by case reports. European Journal of Dermatology, Vol. 21, No. 2, pp. 147-155.

[13] Pappas I. P. I., Keller T., Mangold S., Popovic M. R., and Dietz V. M. M. 2004. A reliable gyroscope-based gait-phase detection sensor embedded in a shoe insole. Sensors Journal, IEEE, Vol. 4, No. 2, pp. 268-274.

[14] Radcliffe C. W. 1994. Four-bar linkage prosthetic knee mechanisms: kinematics, alignment and prescription criteria. Prosthetics and Orthotics International, Vol. 18, pp. 159-173.

[15] Rueterbories J., Spaich E. G., Larsen B., and Andersen O. K. 2010. Methods for gait event detection and analysis in ambulatory systems. Medical Engineering and Physics, Vol. 32, No. 6, pp. 545-552.

[16] Schmalz T., Blumentritta S., and Jaraschb R. 2002. Energy expenditure and biomechanical characteristics of lower limb amputee gait: The influence of prosthetic alignment and different prosthetic components Gait & Posture, Vol. 16, No. 3, pp. 255 - 263

[17] Sin S. W., Chow D. H., and Cheng J. C. 2001. Significance of non-level walking on transtibial prosthesis fitting with particular reference to the effects of anterior-posterior alignment. Journal of Rehabilitation Research and Development, Vol. 38, No. 1, pp. 1-6.

[18] Tong K. and Granat M. H. 1999. A practical gait analysis system using gyroscopes. Medical Engineering & Physics, Vol. 21, No. 2, pp. 87-94.

[19] Zahedi M. S., Spence W. D., Solomonidis S. E., and Paul J. P. 1986. Alignment of lower-limb prostheses. J Rehabil Res Dev., Vol. 23, No. 2, pp. 2-19.

www.arpnjournals.com