Gait Analysis with Kanri Distance Calculator following Anterior Cruciate Ligament Reconstruction

H.Sakeran¹, N.A. Abu Osman²,³, M.S. Abdul Majid¹, Wan Azani Mustafa⁴, Syed Zulkarnain Syed Idrus⁵

¹School of Mechatronic Engineering, Universiti Malaysia Perlis, Malaysia
²Centre for Applied Biomechanics, Department of Biomedical Engineering, Faculty of Engineering, University of Malaya, Malaysia
³The Chancellery, University of Malaysia Terengganu, Terengganu, Malaysia
⁴Faculty of Engineering Technology, University of Malaysia Perlis, UniCITI Alam Campus, Sungai Chuchuh, 02100 Padang Besar, Perlis, Malaysia
⁵Center of Excellence Geopolymer and Green Technology, Universiti Malaysia Perlis, 01000 Kangar, Perlis, Malaysia.

hamzahsakeran@unimap.edu.my

Abstracts. Anterior Cruciate Ligament (ACL) injury is very prevalent in the field of orthopaedics, particularly in sports. Different parameters can be used to forecast an Anterior Cruciate Ligament (ACLR) patient's health condition. The aim of this research is to use Mahalanobis Taguchi System (MTS) methodology to identify useful biomechanical variables from multivariate parameters through Kanri Distance Calculator (KDC). This study analyzed biomechanical variables based on the knee flexion and extension moment and peak vertical ground reaction force from kinetic parameters; phase swing / stance, step and step length and gait velocity from spatial temporal parameter; range of motion from kinetic parameters. This experiment engaged 15 healthy subjects and 10 ACL reconstructed patients. Then, by optimizing the KDC, the 9 attributes are reduced to 7, which are knee flexion and extension moment, speed, step length and stance / swing phase. Key attributes such as swing time and moment of knee flexion are identified as optimal variables of impact in the population. KDC extends our understanding to the correlation of characteristics and enables individual diagnosis to be performed. Then the suitable rehabilitation protocol can be objectively suggested for quicker recovery to specific subjects.

1. Introduction
Over 250,000 individuals were injured with anterior cruciate ligament (ACL) [1]. There has been a substantial rise in the amount of individuals receiving ACL reconstruction (ACLR) from 1994 to 2016, according to studies undertaken by Mall et al. [2]. Different parameters can be used to forecast an ACLR patient's health situation. Schliemann et al. released a paper in which the patient with ACLR had reduced vertical ground response force (VGRF) due to extreme weight acceptance causing pain on the impacted limb K;NJM [3]. Recent evidence suggests that the ACLR knee is going to have a lower knee moment because the affected knee cannot bear higher loading [4]. Previous trials by Schliemann et al. also revealed that patients with ACLR had decreased movement variety (ROM)
during the posture and swing stage relative to the healthy lower limb due to its limited flexibility and expansion capability [3].

The ACLR patient normally walks slower to control joint loading than the healthy group [5]. The patient with ACLR has shorter length of step since their knee has difficulty to fully extending [6]. The stance time will vary from 58% to 61%, while the swing time will vary from 39% to 42% in natural cadence [7]. This obviously showed that when expressed in the stance / swing proportion, the stance phase will usually be higher than the swing phase [7]. The authors' studies from above concluded that from kinetics peak VGRF, knee flexion, and extension moment; kinematics ROM; gait speed, stance / swing ratio, stride and step length from spatial temporal parameters will change gait pattern after ACLR. Consequently, on the basis of these multivariate parameters, doctors and physiotherapists consume lots of time in accessing patients. For example, the qualitative evaluation by scoring the Subjective Knee Form and observation raised the question of forecast reliability and precision. The absence of an effective tool in analyzing the biomechanical parameter relationship impedes the process of rehabilitation [8].

The Mahalanobis Taguchi System (MTS) methodology developed by Taguchi in 1936 has thus raised the major concern for promoting the healthcare system [9]. It is a systematic data mining method designed to classify information on a measurement scale. A Mahalanobis Space (MS) measurement scale is designed as a reference point. The measurement scale precision is validated as an abnormal point through the specified Mahalanobis Distance (MD). The Orthogonal Array (OA) and Signal-to-Noise (S / N) ratio optimize the useful parameter and identify it. The positive gain parameter is maintained while the negative is excluded [8–13]. As a consequence, MTS is capable of reducing multivariate parameters, identifying important characteristics, understanding the correlation between characteristics and performing individual diagnosis.

2. Mahalanobis Taguchi System

A measurement scale was constructed by using MD. The MD computed for normal group known as MS. Taguchi method, included OA and S/N ratio were applied to optimize the system. As a result, the MTS was formed [9]. Generally, there are four steps in MTS and well described in Fig.1 [8–13].

![Four Steps in Mahalanobis Taguchi System (MTS)](image)

**Figure 1.** Four steps in Mahalanobis Taguchi System

Step 1: A measurement scale of MS is constructed as reference point.
- The normal variable is defined.
- The data of the control group is collected.
- The \( \bar{X}_I \) as mean of variable is calculated by using Equation 1.
- The normal variable is standardized by subtracting the mean variable as shown in Equation 3, followed by dividing the standard deviation as shown in Equation 2. The \( \bar{X}_I \) and \( n \) are denoted as...
normal variable and number of observations respectively. The $x_{ij}$ where i-th variable and j-th observation is denoted.

$$\bar{x}_i = \frac{\sum_{j=1}^{n} x_{ij}}{n}$$  \hspace{1cm} (1)$$

$$s_i = \sqrt{\frac{\sum_{j=1}^{n} (x_{ij} - \bar{x}_i)^2}{n-1}}$$  \hspace{1cm} (2)$$

$$z_{ij} = \frac{x_{ij} - \bar{x}_i}{s_i}$$  \hspace{1cm} (3)$$

- The MD computed for normal group known as MS by applying Equation 4. The $c^{-1}$, k and $T$ are denoted as inverse of correlation matrix, number of variables and transpose of vector respectively.

$$D_j^2 = MD_j = \frac{1}{k} \times Z_{ij} \times c^{-1} \times Z_{ij}$$  \hspace{1cm} (4)$$

$$c = \frac{1}{(n-1) \sum_{j=1}^{n} z_{ij}z_{ij}^t}$$  \hspace{1cm} (5)$$

In the literature of Wang et al., the value of MD in MS, also known as unit space is 1 [10].

Step II: The accuracy of measurement scale is validated through the defined MD as abnormal point.

- The abnormal variable is defined. The MD of the abnormal group is required to be calculated to separate both normal and abnormal group by comparing to the reference point. The variables that fall outside of the reference group, also known as MS are grouped as abnormal group. Most research in MTS emphasized the greater MD values of abnormal observation than normal observation is considered as good MD scale [9–11]. MD provides correlation among the variables [10,14].

Step III: The OA and S/N ratio used to optimize the system.

- OA is a design matrix which combine various level of variables and run in the experiment to investigate the response of variables. OA consists of two levels which are inclusive (level 1) and exclusive level (level 2). The computed MD in Equation 4 is applied in Equation 6 to investigate the response of variables, meanwhile, to test its degree accuracy of measurement scale. d is denoted as abnormal observation and j=1, 2 ..., d

$$\frac{S}{N} = -10 \log_{10} \left[ \frac{1}{d} \sum_{j=1}^{d} \frac{1}{MD_j^2} \right]$$  \hspace{1cm} (6)$$

Taguchi and Rajesh pointed out in an analysis into MTS that the higher the S / N value, the better the performance. The severity level of the abnormal group is not generally known. The fact that undeniable, however, is that the required measurement scale of MD is always larger than normal group. The higher MD value is good for separating the abnormal from the normal group. The higher value of the S / N ratio is therefore adequate to define the abnormal condition and to optimize the system better. For positive computed gain, the variable will be held while removed for negative computed gain, as calculated using Equation 7.

$$Gain = \frac{S}{N_{level1}} - \frac{S}{N_{level2}}$$
Step IV: Forecasting and future diagnosis.
- The key attributes will be identified.
- The MTS reduce the number of attributes.
- The MTS enable the understanding of the correlation between attributes.
- It can perform the diagnosis individually thus design preferable rehabilitation protocol.

3. Kanri Distance Calculator (KDC™)
KDC is the statistical tool that evaluate the multivariate parameters by MTS methodology. The proprietary combination of patented statistical and method techniques provided by Kanri offers an exceptionally strong and insightful capacity to assess big information sets with various variables. While many instruments assess models and dynamics for big information sets, only the KDC™ enables consumers to know where they are in relation to a required target state and each variable's particular contribution to the general distance from the target state. The Kanri model not only calculates the connection of factors within the general information set, but also teases the correlation between each of them mathematically [7].

4. Related Work
4.1. Subject Selection
15 healthy subjects were selected for the healthy group (target group). These subjects had no prior history of lesions, surgeries or neuropathy with lower extremities. The HG consisted of 15 males. Meanwhile, patients with ACLR from the Rehab and Physiotherapy Unit of Hospital Tuanku Fauziah at Kangar, Perlis, were considered for this study as off-target group. Ten patients with unilateral primary ACLR were chosen for the ACLR group. This off-target group was composed of 10 males.
All patients underwent similar rehabilitation procedures, beginning passive and active mobilisation after the operation. Ethical approval was granted by the University of Malaysia Perlis, and the participants provided written informed consent.

4.2. Data recording
Subjects were asked to walk along an eight-meter walkway six times. To allow adaptation to the instrumentation and task, the first two laps were not assessed. The final four laps were assessed to fully capture four gait cycles information using the right limb in the HG and the injured limb in the PG. The trial was conducted within a Motion Lab at University Malaysia Perlis. Before testing, retro-reflective markers were put over bony pelvic landmarks and lower extremities, and arrays of markers were connected using elastic wrap to the thighs and shanks. The markers were captured using an optical 5-camera motion capture system (Oqus, Qualisys AB, Gothenburg, Sweden). The static trial of subjects was captured in 2 seconds at 120 Hz. This was followed by the walking motion of the subjects; the dynamic trials were captured in 8 seconds at 480 Hz. Two embedded force plate (Bertec, Worthington, Ohio, USA) detected the vertical ground reaction force while the subject accomplished a number of walks at their own pace. At least five success trials were captured and post-processed using QTM software (Qualisys AB, Gothenburg, Sweden). The kinetics, kinematics and spatial temporal parameters of the trial were generated in Visual 3D (Version 6.0; C-Motion, Inc., Germantown, MD).

4.3. Data Analaysis - KDC
Nine attributes from three main parameters are computed in KDC and the result can be analyzed based on MD. There are 15 normal and 10 ACLR subjects with nine attributes arranged well and saved in CSV Excel format. These nine attributes are composed of the peak VGRF, knee flexion and extension moment from kinetic parameter; the range of motion from kinematic parameter; the speed, stride and step length, stance/swing phase from spatial temporal parameter. The steps of using KDC is described as below:
Step I: A measurement scale of MS is constructed as reference point. The dashboard of the KDC is displayed as Fig. 2 and normal data in CSV format are loaded as target group into KDC. The target group is constructed for normal group based on 15 subjects by applying Equation 4 to obtain MS.

Step II: The accuracy of measurement scale is validated through the defined MD as abnormal point. The ACLR data are loaded as off target group into KDC. The off-target value is constructed for abnormal group based on 10 subjects by applying Equation 4 to obtain MD for validating the measurement scale.

Step III: The optimization by using the Orthogonal Array (OA) and Signal-to-Noise (S/N) ratio. The nine attributes are allocated for nine columns. The experiments are run at each row. OA consists of two level which are inclusive and exclusive. The attributes will be selected if in inclusive level while excluded if in exclusive level. This condition will be further evaluated by applying S/N ratio equation, as denoted in Equation 6. The attributes with positive gain will be kept, on the other hand, the attributes with negative gain will be excluded.

Step IV: The variables of importance are identified from multivariate attributes. The significant parameters can be identified. The root cause analysis (RCA) can be interpreted by showing each contribution ratio. Each subject can then be diagnosed individually.

5. Results and Discussions
 Basically, the results are explained based on the four steps of MTS methodology with the aiding of computed charts and table from KDC. The appropriate and desired rehab protocol is then suggested to every subject based on the diagnosis.

5.1. Comparison between Normal and ACLR Subjects
 The target group is denoted as normal group which represented by the subjects who have healthy limb. The off-target group also known as abnormal group which represented by the subject who have ACL reconstructed limb. In Step I, the reference group is constructed based on 15 normal subjects by using Equation 4. Fig. 3 show the experimental data on MS, which is 0.933, and can be rounded off to 1.0 since it is also known as unit space [10]. In Step II, as can be seen from Fig. 4, the MD value for ACLR off target based on ten subjects are calculated by applying Equation 4. The average of MD value is 26.05. The calculated MD is well separate both normal and abnormal group by comparing to the reference point, as illustrated in Fig. 5. The target group valid with 100%, as denoted in Fig. 6. The measurement scale will only be validated if only the computed MD for off target group is greater than MS. This clearly indicated by the MD value (26.05) for off target group is greater than target group (0.93).

In Step III, KDC display the off-target participant distances histogram, as denoted in Fig. 7. Ten ACLR subjects are distributed based on distances. The distance is ranged from the highest, 150 to lowest 0. There is one subject lie in the distances of 150 to 120; one subject in the distance of 90 to 60 and eight subjects in distance of 30 to 0. The histogram depicted in Fig. 7 provide an overview will be further separated into detail with provided distance variable contribution, as represented in Fig. 8, Fig. 9 and Fig. 10. Subject 3 and 9 with the distance of 150 to 120 and 90 to 60 respectively, as shown in
Fig. 8 and Fig. 9. Both of these subjects have distance far from the origin. Therefore, both of this ACLR subjects have greater degree of abnormality as compared to the other subjects, as depicted in Fig. 10.

The root cause analysis with variable contribution ratio, as denoted in Fig. 8, Fig. 9 and Fig. 10 provide a better visualization for users to determine the key factor. From the Fig. 9, we can see that stride length (strideL) is the main contribution for subject 9. Therefore, an appropriate rehabilitation protocol should be suggested to particular subject 9 to improve the stride length. The distance variable contribution of each subjects can also be represented in table form, as denoted in Fig. 11. We can apparently notice that the swing time is the driving population behavior in the population. The variable will be highlighted as red impact if exceed an acceptable range while highlighted as blue impact if lower than the acceptable range. In addition, the yellow impact shows the in-control variable. Interestingly, for subject 6, the swing time is the main attribute followed by stance time. In this case study, the swing time need to be reduced and stance time increased to achieve in-control condition. This mean that KDC able to help to diagnose patients individually.
Figure 7. Off Target participant distances histogram

Figure 8. Off Target participant distances of 150 to 120 for subject 3

Figure 9. Off Target participant distances of 90 to 60 for subject 9

Figure 10. Off Target participant distances of 30 to 0 for the rest of the subjects
Step IV:
The KDC able to perform diagnosis individually and desired rehab protocol can be suggested for particular subjects. Several biomechanical parameters are assessed with a total of nine features based on sets of laboratory equipment and software such as kinetics, kinematics and spatial temporal. Identifying important characteristics from multivariate parameters is the most obvious results to arise in this study. Then, by optimizing the KDC, the nine attributes are reduced to seven, which are knee flexion and extension moment, speed, step length and stance / swing phase. Key characteristics such as swing time and moment of knee flexion are recognized as ideal factors of effect in the population.

In addition, the KDC extends our understanding to the correlation of characteristics in order to improve patient therapy and diagnosis. In this research, KDC's remarkable contribution is its ability to perform individual diagnosis. Then the nine features are reduced to seven by optimizing the KDC, which are moment of knee flexion and extension, speed, duration of step and stance / swing phase. Key features such as swing time and knee flexion moment are acknowledged in the population as optimal impact variables. Furthermore, the KDC extends our knowledge to attribute correlation to improve the treatment and diagnosis of patients.

6. Conclusion
The notable contribution of KDC in this research is its ability to conduct individual diagnosis. Based on KDC assessment, the suitable rehabilitation protocol can be suggested to specific topics for quicker recovery to original functional level. More generally, it is suggested that KDC be applied by MTS methodology to support diagnosis in healthcare systems such as rehabilitation of ACL reconstructed patients. This statistical tool that is purely quantitative and effective is easily interpreted. It thus assists physicians and physiotherapists in the short-term diagnosis and suggestion of rehabilitation protocol, and with important characteristics perform objectively.

Acknowledgements
The authors would like to acknowledge the supporting staff at the Biomechanics Lab of University Malaysia Perlis for assistance in data preparation and data collection. We would also like to thank the Physiotherapy Unit of Hospital Tuanku Fauziah for providing the physical therapy treatments for our subjects. The University Malaysia Perlis Review Board approved this study.

References
[1] Sanford B a, Zucker-Levin A R, Williams J L, Mihalko W M and Jacobs E L 2012 Principal component analysis of knee kinematics and kinetics after anterior cruciate ligament reconstruction. *Gait Posture* 36 609–13
[2] Mall N A, Chalmers P N, Moric M, Tanaka M J, Cole B J, Bach B R and Paletta G A 2014 Incidence and Trends of Anterior Cruciate Ligament Reconstruction in the United States *Am. J. Sports Med.* 42 2363–70
[3] Schliemann B, Glasbrenner J, Rosenbaum D, Lammers K, Herbot M, Domnick C, Raschke M J and Kösters C 2017 Changes in gait pattern and early functional results after ACL repair are comparable to those of ACL reconstruction Knee Surgery, Sport. Traumatol. Arthrosc.

[4] Zabala M E, Favre J, Scanlan S F, Donahue J and Andriacchi T P 2013 Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. J. Biomech. 46 515–20

[5] Kaur M, Ribeiro D C, Theis J-C, Webster K E and Sole G 2016 Movement Patterns of the Knee During Gait Following ACL Reconstruction: A Systematic Review and Meta-Analysis Sport. Med. 1–27

[6] Gao B and Zheng N (Nigel) 2010 Alterations in three-dimensional joint kinematics of anterior cruciate ligament-deficient and -reconstructed knees during walking Clin. Biomech. 25 222–9

[7] Winter DA 1987 The biomechanics and motor control of human gait

[8] Su C T, Wang P C, Chen Y C and Chen L F 2012 Data mining techniques for assisting the diagnosis of pressure ulcer development in surgical patients J. Med. Syst. 36 2387–99

[9] Taguchi G and Rajesh J 2000 New Trends in Multivariate Diagnosis Sankhyā Indian J. Stat. Ser. B 62 233–48

[10] Wang H, Chiu C, Su C and Wang H 2016 DATA CLASSIFICATION USING THE MAHALANOBIS — TAGUCHI J. Chinese Inst. Ind. Eng. 21 606–18

[11] Taylor P, Woodall W H, Koudelik R, Tsui K, Kim S B, Stoumbos G, Carvounis C P, Woodall W H and Koudelik R 2012 A Review and Analysis of the Mahalanobis - Taguchi System 45 37–41

[12] Muhamad W Z A W, Jamaludin K R, Ramlie F, Harudin N and Jaafar N N 2018 Criteria selection for an mba programme based on the mahalanobis taguchi system and the kanri distance calculator IEEE Student Conf. Res. Dev. Inspiring Technol. Humanit. SCOREd 2017 - Proc. 2018-Janua 220–3

[13] Jin X and Chow T W S 2013 Anomaly detection of cooling fan and fault classification of induction motor using Mahalanobisâ€”Taguchi system Expert Syst. Appl. 40 5787–95

[14] Cudney E A, Hong J, Jugulum R, Paryani K, Ragsdell K M, Taguchi G, Rolla M and Missouri U S A 2007 An Evaluation of Mahalanobis-Taguchi System and Neural Network for Multivariate Pattern Recognition JISE 1 139–50