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## Gait assessment in unicompartmental knee arthroplasty patients: Principal component modelling of gait waveforms and clinical status

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### Abstract

The reduction and analysis of gait waveform data is a significant barrier to the clinical application of gait analysis. Principal component modelling of gait waveform data reduced the waveform data to measures of distance from normal and these distance measures were shown to be sensitive to changes in gait pattern associated with knee osteoarthritis and its treatment by unicompartmental arthroplasty. Principal component models were developed for eight knee kinematic and kinetic gait waveforms of a group of 30 normal elderly subjects. Each model consisted of a set of loading vectors, principal component scores and residuals. The loading vectors revealed the structure of the model and the scores and residuals were used as the distance measures about which confidence intervals were developed. Pre-operative and post-operative gait data from 13 unicompartmental arthroplasty (UCA) patients were used to demonstrate the application of the principal component models to pathological gait data. A gait score was developed to indicate the overall assessment of the kinematic and kinetic gait measures by the principal component models. This gait score was shown to agree with the

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clinical status as measured by the Knee Society Score (pre-op:  $r_s = 0.86$ ; post-op:  $r_s = 0.73$ ). Thus, the differences in gait pattern detected by the principal component models were clinical relevant. © 1999 Elsevier Science B.V. All rights reserved.

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## 1. Introduction

The knee is one of the most common sites for osteoarthritis (OA), and accounts for more pain and disability than any other joint (Felson, 1987). While the main indication for knee arthroplasty in the treatment of OA is pain, a further objective is to improve the patient's functional ability. Advocates of unicompartmental arthroplasty (UCA) as an effective treatment for moderate unicompartmental osteoarthritis maintain that a physiologically functioning knee can be obtained (O'Connor & Goodfellow, 1991; Kozinn & Scott, 1989). Most of the studies investigating these claims have evaluated the treatment using clinical outcome measures such as the Hospital for Special Surgery (HSS) or the Knee Society Score (KSS) (Weale & Newman, 1994; Laurencin, Zelicof, Scott & Ewald, 1991; Scott, Cobb, McQueary & Thornhill, 1991; Stockelman & Pohl, 1991; Marmor, 1988). Gait analysis is a direct evaluation of the knee that can provide information in addition to those clinical outcome measures. Despite this, there have been relatively few gait studies examining the UCA patient group. These gait studies have focussed on either a few simple gait measures (Weidenhielm, Svensson, Brostrom & Rudberg, 1992; Weinstein, Andriacchi & Galante, 1986) or did not relate the gait measures to clinical status (Chassin, Mikosz, Andriacchi & Rosenberg, 1996; Whittle & Jefferson, 1989).

One reason for the limited clinical application of gait analysis is due to problems dealing with the tremendous amount of data that are produced by current gait analysis systems. The reduction of gait data to clinically useful information continues to challenge researchers in gait analysis. There are generally two approaches to the reduction of gait data. The first, which is the most commonly used, is to extract parameters (peak values, for example) from the waveforms and the other is to characterise the entire waveform (Schnitzer, Popovich, Andersson & Andriacchi, 1993; Whittle & Jefferson, 1989; Chao, Loughman, Schneider & Stauffer, 1983; Stauffer, Chao & Gyory,

1977). Waveform-based analysis methods have the advantage of utilising the entire gait cycle data to detect subtle changes in gait patterns not discernible when examining curve parameters. These methods include Fourier series, neural network classifiers and pattern recognition techniques (Holzreiter & Kohle, 1993; Kadaba, Ramakrishnan, Jacobs, Goode & Scarborough, 1993; Gioftos & Grieve, 1993; Lasko-McCarthy, Beuter & Biden, 1990; Wong, Simon & Olshen, 1983).

Principal component analysis is a statistical tool that has become quite popular in the analysis of multivariate data. Some investigators have applied principal component analysis to waveform data as an intermediate analysis technique to be followed by cluster analysis or correspondence analysis (Shiavi & Griffin, 1981). It has also been used to derive fundamental waveforms (basic or loading vectors) that relate to biomechanical attributes (Wootten, Kadaba & Cochran, 1990). Deluzio, Wyss, Zee, Costigan and Sorbie (1997) demonstrated a method of constructing principal component models to characterise normal subjects' gait waveforms. The models reduced the waveform data to statistical measures of distance which indicated whether or not a patient had a gait pattern that is similar to that of the average trajectory of the normal subjects.

Any new analytical methods developed to aid in the analysis of complex data available from modern gait labs must be challenged to provide interpretation that is clinically relevant. In this study principal component models were applied to a sample of OA patients treated with UCA. Construct validity was established by comparing the principal component model results to the clinical outcome measures. Thirteen patients were evaluated pre-operatively and at one year post-operatively using gait analysis and clinical outcome. The gait pattern of the patients, as evaluated by the principal component models, was compared to the KSS, a clinical measure.

## **2. Methods**

The 13 patients studied were chosen from referrals to outpatient clinics of two local hospitals. All had painful, disabling osteoarthritis of one or both knees principally affecting the medial side. These patients met the usual criteria to qualify for a unicompartmental replacement including: weight not over 140 kg, presence of intact cruciate ligaments, and knee arthritis not rheumatoid. The surgery consisted of a standard unicompartmental replacement using the Miller-Galante® (Zimmer) implant components. In no case were obvious

operative complications encountered. The control group was composed of 30 asymptomatic older volunteers with no history of arthritic disease, or record of surgery to the lower limbs. Ethics board approval was obtained prior to the involvement of any of these subjects in this study.

The clinical status was measured using the KSS administered by a research assistant trained and qualified in the specific contents of the instrument. The KSS (Insall, Dorr, Scott & Scott, 1989) is subdivided into two parts: a knee score and a function score. By adding the knee and function scores a single score, out of a possible 200 points for a fully functional pain free knee, is available to indicate the patient's clinical status.

The gait pattern was studied using a 3D gait analysis system that has been previously described and validated (Li, Wyss, Costigan & Deluzio, 1993; Deluzio, Wyss, Li & Costigan, 1992; Costigan, Wyss, Deluzio & Li, 1992). This system uses optoelectronic motion tracking, standardised radiographs, force plate measurements and anthropometrics to calculate the 3D components of knee angles, net reaction moments and bone-on-bone forces. The subject is radiographed immediately following the gait assessment wearing lead beads affixed at the positions of the surface markers. In this way knee alignment data and bone geometry can be incorporated into the gait analysis. This allows a more accurate transformation from surface marker locations to joint centres as well as incorporating relevant bone anthropometry into a subject-specific knee model. The gait analysis provides kinematic and kinetic measures of knee joint biomechanics including 3D relative angles, net moments, and bone-on-bone forces. The sign convention for these measures follows an anatomically based co-ordinate system embedded in the proximal tibia along the lateral–medial (LM), posterior–anterior (PA), and distal–proximal (DP) directions. The relative knee angles as well as net joint reaction moments are measured about these axes according to a right-hand rule, and bone-on-bone forces are measured along the axes. The naming of the axes indicates the positive direction; for example the PA axis is directed from posterior to anterior. Principal component models were developed for each of these kinematic and kinetic gait measures for the normal subjects. The details of the development and application of the principal component models have been described previously (Deluzio et al., 1997). A schematic of the process is shown in Fig. 1. In this example the waveform data are reduced to three principal components. Two statistical distance measures ( $T^2$  and  $Q$ ) are derived to indicate the similarity of each subject's waveform to the average trajectory of the normal subjects. Confidence intervals for the  $T^2$  and  $Q$  values are derived from the 30 normal subjects and are used as a reference for comparing the patient gait data ( $\alpha = 0.05$ ).

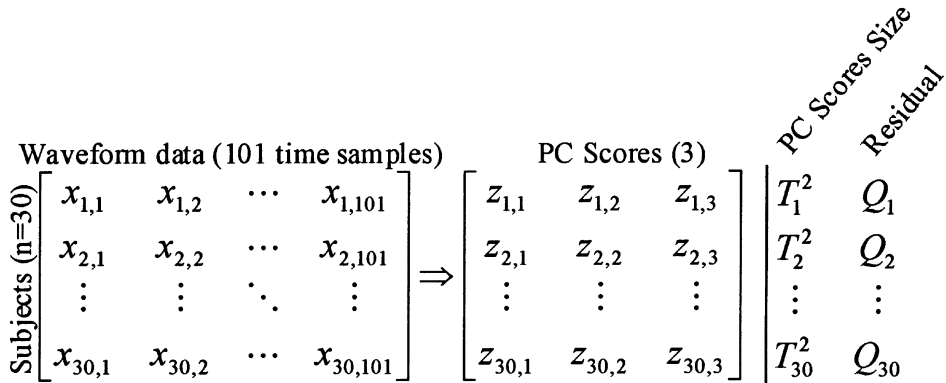


Fig. 1. Schematic of PC modelling. The waveform data of 30 normal subjects are transformed from 101 data points per subject to three principal components. The  $T^2$  are a measure of the size of PC scores and the  $Q$  values measure the size of the residuals. This process is performed for each of the eight gait measures.

The principal component models were applied to the patient gait data to obtain a set of principal component scores and residuals for each of the patients. As with the normal subjects, a  $T^2$  value was calculated from the scores and a  $Q$  value was calculated from the residuals. By comparing the  $T^2$  and  $Q$  values to the confidence intervals derived from the normal subjects, the patient’s pre-operative and post-operative gait waveforms could be assessed as either within or not within the normal range. The overall patient gait assessment is provided by examining the principal component models of all the kinematic and kinetic gait measures. It was this overall assessment which was compared to the KSS.

### 3. Results

All but one patient (P5) showed marked clinical improvement as indicated by the KSS. Patients improved by an average KSS of 43 points. A paired  $t$ -test showed this change to be significant at the  $p < 0.01$  level.

Table 1 provides the overall gait assessment of the patients using the principal component models developed from the normal subjects. The table is coded to provide an immediate evaluation of each gait measure. A cross,  $\times$ , indicates a significant difference from normal while a check,  $\checkmark$ , indicates that the waveform pattern is within normal limits. A significant difference from normal implied that either (or both) of the  $T^2$  or  $Q$  values were not within the 95% confidence intervals determined by the normal subjects.

Table 1  
Patient assessments<sup>a</sup>

UCA patients	KSS/200	Bone-on-bone forces			Net reaction moments			Knee angle		Gait score
		PA <sup>b</sup>	LM <sup>b</sup>	DP <sup>b</sup>	PA <sup>b</sup>	LM <sup>b</sup>	DP <sup>b</sup>	PA <sup>b</sup>	LM <sup>b</sup>	
P1	Pre	75	×	×	×	×	×	×	×	0
	Post	145	×	✓	✓	✓	×	✓	✓	6
P2	Pre	95	×	✓	×	×	×	×	×	1
	Post	107	✓	✓	×	✓	×	×	×	4
P3	Pre	105	✓	×	×	×	×	×	×	1
	Post	138	×	×	✓	×	✓	×	✓	4
P4	Pre	110	✓	✓	×	✓	×	✓	✓	5
	Post	160	✓	✓	×	✓	×	✓	✓	6
P5	Pre	104	×	✓	✓	×	×	✓	×	4
	Post	99	×	×	✓	×	×	✓	×	2
P6	Pre	135	✓	✓	✓	✓	✓	✓	✓	8
	Post	184	✓	✓	✓	✓	✓	✓	×	7
P7	Pre	93	×	×	×	×	×	✓	×	1
	Post	114	×	×	×	×	×	×	×	0
P8	Pre	126	✓	✓	×	✓	×	×	✓	5
	Post	169	×	×	×	×	×	✓	×	1
P9	Pre	64	×	×	×	×	×	✓	×	1
	Post	138	×	×	✓	×	×	✓	×	3
P10	Pre	85	×	✓	×	×	×	×	×	1
	Post	185	✓	✓	×	✓	✓	✓	✓	7
P11	Pre	91	×	✓	×	×	✓	✓	×	3
	Post	144	×	✓	✓	✓	×	✓	×	5
P12	Pre	149	×	✓	✓	✓	✓	✓	✓	7
	Post	191	✓	✓	✓	✓	✓	✓	✓	8
P13	Pre	139	×	✓	✓	✓	✓	✓	✓	7
	Post	160	✓	✓	✓	✓	✓	✓	✓	8

<sup>a</sup> A × indicates significantly different from normal, while ✓ indicates that waveform pattern is similar to the normal pattern. The gait score is the number of gait variables (of a possible 8) that are similar to the normal pattern. It is equal to the number of ✓'s in the row.

<sup>b</sup> The letters PA, LM, and DP refer to posterior/anterior, lateral/medial and distal/proximal directions. Thus, a DP bone-on-bone force is the force at the proximal tibia considered positive if acting from distal to proximal. Moments and angles are measured these directions using the right-hand rule.

A simplified 'gait score' was developed to measure the overall change in the patient's gait pattern. The score was calculated as the number of gait measures that were within normal limits (i.e. the number of checks, ✓, for each

assessment). For example, patient P1 in Table 1 had a pre-operative gait score of 0 indicating that none of the gait measures were within normal limits; whereas, the post-operative gait score was 6 reflecting the improvement in six gait measures. The pre-operative gait scores ranged from 0 to 8 revealing large differences in the gait patterns among the 13 patients. While the post-operative range in gait scores was similar; nine out of 13 patients showed an improvement in their overall gait pattern. A comparison between the pre-operative and post-operative gait scores revealed no significant change (Wilcoxon signed rank test  $p > 0.166$ ).

Table 1 revealed that patients with similar gait scores could differ in which gait measures were similar to normal. For example, consider the pre-operative and post-operative gait assessments of patients P2 and P3. Selected gait waveforms for these patients are presented in Fig. 2. Both patients had a pre-operative gait score of 1, which then improved to 4 post-operatively. For patient P2 the improvements were for the most part associated with kinetic gait measures; that is, joint moments and forces. The kinematics, joint angles, were unchanged by the UCA. The opposite was true for patient P3 whose improvements were primarily kinematic. In this case the knee angles were improved, but only the sagittal joint moment and distal proximal joint force were improved post-operatively. It was also observed that the post-operative KSS for patient 3 was over 30 points higher than that of patient 2.

The relationship between the gait score and the clinical status (KSS) was examined pre-operatively and post-operatively (Fig. 3). The pre-operative relationship was very strong (Spearman rank correlation coefficient,  $r_s = 0.87$ ;  $p < 0.001$ ) indicating a direct correspondence between the gait pattern as measured by the principal component models and the patient's clinical status as measured by the KSS. The post-operative relationship, while present, was not as strong ( $r_s = 0.70$ ;  $p < 0.01$ ). The change in the gait score was also examined in relation to the change in KSS and no relationship was found ( $r_s = 0.47$ ;  $p > 0.1$ ).

#### 4. Discussion

In previous work it was demonstrated that principal component analysis could be used to detect and interpret differences in gait waveforms (Deluzio et al., 1997). Using principal component analysis gait waveform data were represented as a set of scores and residuals that were reduced to two statistical distance measures:  $T^2$  and  $Q$ . Confidence intervals about  $T^2$  and  $Q$

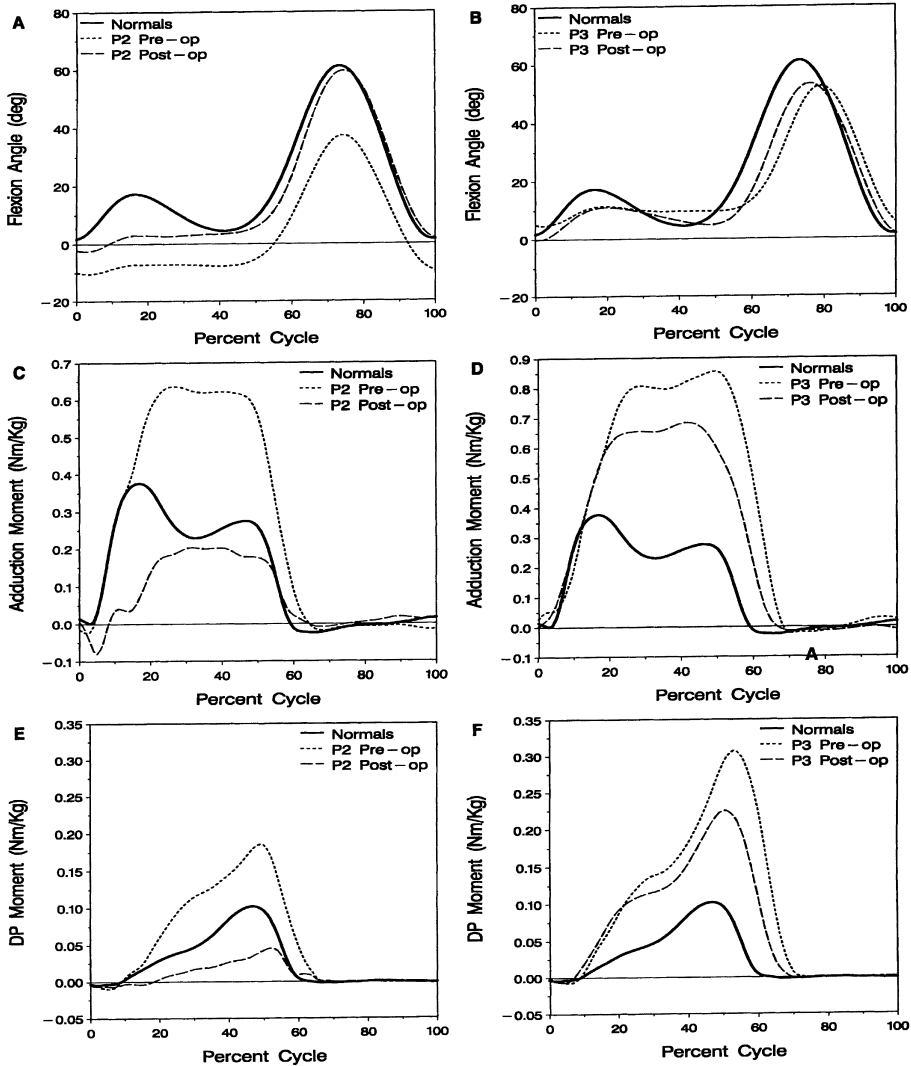


Fig. 2. Gait waveforms for patients P2 and P3. The pre-operative and post-operative patient gait waveform data as well as the average of the 30 normal subjects for selected gait waveforms. The results of the principal component analysis of the patient gait waveforms are described in Table 1. (A–B) flexion angle data (knee angle about LM axis) for P2 and P3. (C–D) adduction moment data (net moment about PA axis) for P2 and P3. (E–F) moment about the distal–proximal (DP) axis of the tibia for P2 and P3.

derived from normal subjects provided limits to which patient gait was compared. The structure of the models provided the interpretation of the difference by identifying the portion of the gait cycle responsible for the



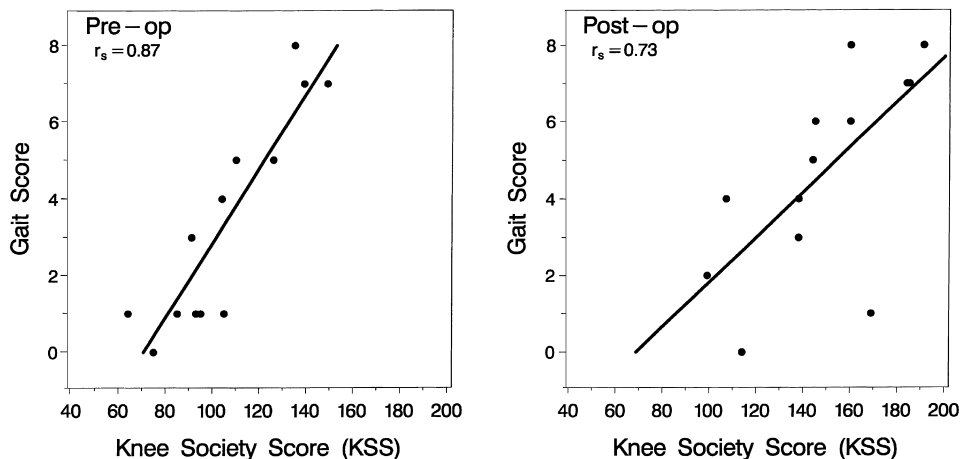


Fig. 3. Gait Score vs. KSS. The gait score represents the number of gait measures that are not significantly different from normal. As eight gait measures were assessed the score can range from 0 to 8. (a) The pre-operative relationship is significant with a Spearman's correlation coefficient,  $r_s = 0.86$  ( $p < 0.001$ ). (b) The post-operative relationship is significant as well ( $r_s = 0.73$ ;  $p < 0.01$ ).

difference. The work presented here demonstrated that the differences detected by the principal component models are correlated with clinical status.

There are limitations to the gait score as a measure of the overall gait pattern. It considers all gait measures and all model parameters (i.e. scores and residuals) equally; however, there is likely a hierarchy of importance among these. Furthermore, information as to the severity of the abnormal gait measure is ignored. The gait score is composed of binary indicators of difference from normal while it may be of use to exploit the severity of the difference. Despite these limitations the gait score was found to be quite useful. The score was developed as a first level evaluation of the information provided by the principal component models. As such, it was a suitable choice due to its simplicity and ease of interpretation.

The gait score was a simple measure that allowed the assessment of the overall gait pattern of the patient by applying principal component analysis to gait measures of knee kinematics and kinetics. The pre-operative gait score was shown to correlate with the pre-operative KSS ( $r_s = 0.87$ ;  $p < 0.001$ ). The differences from normal detected by the principal component models corresponded to the clinical status of the patient. The post-operative relationship was not as strong ( $r_s = 0.73$ ), and there was no correlation between the change in gait score and the change in KSS. This lack of correlation was due to the increased scatter in the post-operative results and the

difference in the regression slopes between the pre-operative and the post-operative data (Fig. 3).

It is of some interest that the KSS relationship with gait was stronger pre-operatively than post-operatively. The KSS instrument has been criticised for being dominated by pain (Dias, 1992). It is reasonable that the pre-operative gait of the patients was related to pain; the severity of the gait deformity being related to the degree of pain. Post-operatively, the pain was reduced if not eliminated altogether. Therefore, the deviations from normal gait would be now less related to the degree of pain and thus to the KSS. The post-operative gait deviations may have been due to some aspect of patient status that the KSS does not capture. It has been shown that gait measures can be altered by things like component placement; that clinical measures are insensitive to (Weinstein et al., 1986). It is possible that the principal component models are sensitive to patient responses to the underlying biomechanics of the resurfaced joint. Pre-operatively, it is the pain that determines the gait pattern, while post-operatively it is the mechanics of the UCA that determine the gait pattern. This may explain why the correlation between the gait score and the KSS changed post-operatively.

The variable success of unicompartmental knee replacement suggests that the mechanics of implantation may be more critical in this procedure than in other types of joint replacement (Rand, 1996). Larger scale clinical studies are needed to confirm this hypothesis.

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