

Changes in frontal plane dynamics and the loading response phase of the gait cycle are characteristic of severe knee osteoarthritis: application of a multidimensional analysis technique

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Abstract

Background. Osteoarthritis of the knee is related to many correlated mechanical factors that can be measured with gait analysis. Gait analysis results in large data sets. The analysis of these data is difficult due to the correlated, multidimensional nature of the measures.

Methods. A multidimensional model that uses two multivariate statistical techniques, principal component analysis and discriminant analysis, was used to discriminate between the gait patterns of the normal subject group and the osteoarthritis subject group. Nine time varying gait measures and eight discrete measures were included in the analysis. All interrelationships between and within the measures were retained in the analysis.

Findings. The multidimensional analysis technique successfully separated the gait patterns of normal and knee osteoarthritis subjects with a misclassification error rate of <6%. The most discriminatory feature described a static and dynamic alignment factor. The second most discriminatory feature described a gait pattern change during the loading response phase of the gait cycle.

Interpretation. The interrelationships between gait measures and between the time instants of the gait cycle can provide insight into the mechanical mechanisms of pathologies such as knee osteoarthritis. These results suggest that changes in frontal plane loading and alignment and the loading response phase of the gait cycle are characteristic of severe knee osteoarthritis gait patterns. Subsequent investigations earlier in the disease process may suggest the importance of these factors to the progression of knee osteoarthritis.

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1. Introduction

Osteoarthritis (OA) of the knee is one of the most common age-related diseases of the musculoskeletal system and is the major cause of pain and disability in the elderly (Dieppe, 1992). Knee osteoarthritis is a dynamic pathological process that involves many interrelated

mechanical and biological factors. The complexity of the relationships between these factors has hindered the understanding of the pathomechanics of knee OA.

Previous gait studies have identified several gait differences in patients with knee OA. OA is associated with changes in gait characteristics that include stride characteristics (i.e. velocity, cadence, and stride length), joint kinematics, and joint kinetics (Andriacchi et al., 1982; Schnitzer et al., 1993; Stauffer et al., 1977). The adduction moment, in particular, has been found to be relevant to knee OA. It has been shown to correlate with

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proximal tibial bone density (Hurwitz et al., 1998), disease severity (Sharma et al., 1998), disease progression (Miyazaki et al., 2002) and surgical outcome (Prodromos et al., 1985; Wang et al., 1990). The static frontal plane alignment angle, the hip knee ankle (HKA) angle, has also been recognized as an important knee OA factor (Olney et al., 1994; Sharma et al., 2000). Knee OA differences have also been found in the dynamic knee flexion moment (Baliunas et al., 2000; Kaufman et al., 2001) and in the range of knee flexion angle during gait (Stauffer et al., 1977; Andriacchi et al., 1982; Schnitzer et al., 1993).

Although most gait data appear as temporal waveforms representing specific joint measures throughout the gait cycle (i.e. joint angles and moments), previous gait studies analysed parameters that were chosen subjectively from gait waveforms. In 1997, Deluzio et al. recognized the strong correlations between the time samples of gait waveforms and introduced principal component analysis (PCA), a multivariate statistical technique, to the analysis of kinematic and kinetic gait waveform measures. The technique considered data from the entire gait cycle, and reduced it to statistical distance measures that indicated the similarity of a subject's gait data to a reference dataset. The authors were able to localize within the gait cycle, pathological deviations from normal gait (Deluzio et al., 1997, 1999). However, PCA was applied to each gait waveform measure individually, ignoring any interrelationships between the gait measures.

The applicability and widespread use of gait analysis as a clinical tool has been hindered by a lack of appropriate gait data analysis techniques for reducing and interpreting large volumes of correlated gait data (Brand, 1992). Interrelationships between gait measures exist. Positive correlations between the dynamic adduction moment and the static frontal alignment angle have been found (Hurwitz et al., 2002; Olney et al., 1994), as well as relationships between body mass index (BMI) and the knee extension moment (Kaufman et al., 2001), and the knee flexion angle and the knee flexion moment (Kaufman et al., 2001).

In this work, the previous PCA waveform analysis techniques developed by Deluzio et al. (1997) were extended to simultaneously analyse multiple waveform measures, as well as discrete measures that are important to knee osteoarthritis. Utilizing two multivariate statistical techniques, principal component analysis and discriminant analysis, the analysis technique retained both the temporal correlation structure of waveform gait measures, and the correlations between the measures. In the development of the multidimensional analysis technique, it was desirable to compare the gait patterns of subjects on either end of the knee OA disease spectrum, patients with severe knee OA and normal subjects, where definite differences between these groups

were expected. The technique could then be generalized to apply to populations with less severe forms of the OA disease process.

2. Methods

2.1. Subject selection and gait analysis

The normal subject dataset consisted of 63 asymptomatic elderly volunteers. These subjects were over 45 years of age, pain-free, had no record of surgery to the lower limb and no evidence or history of arthritic disease at the time of testing. The patient population consisted of 50 elderly patients with severe knee osteoarthritis (OA), evaluated within 6 months prior to total knee replacement surgery. Comorbidity was not assessed, but is probable in people with end-stage osteoarthritis. Subject anthropometrics are summarized in Table 1.

Three-dimensional gait patterns of subjects were studied with an optoelectronic gait analysis system (Costigan et al., 1992) that incorporated a standardized radiographic technique (Siu et al., 1991). Standardized radiographs for all subjects were taken with the knee in a natural standing position, and included an anterior-posterior view of the hip and knee as well as a lateral knee view for the test leg only. X-rays were used to measure static knee alignment, geometry and muscle moment arms, and to move the positions of the motion tracking system markers to their predetermined bone landmarks. This allowed for accurate transformations from surface marker locations to joint centers. Three-dimensional locations of six infra-red light emitting diodes were measured at 50 Hz. A force plate was synchronized with the global coordinate system of the camera with a motion calibration frame.

An inverse dynamics procedure was used to calculate three-dimensional knee joint angles, moments and forces with respect to the tibia plateau. The three-dimensional sign convention for the angles, moments and forces follows an anatomically based coordinate system. The three principal axes were termed PA (posterior–anterior), LM (lateral–medial) and DP (distal–proximal). Knee angles were defined according to Grood and Suntay (1983) and moments were expressed as net external knee joint moments (Costigan et al., 1992).

Scaled radiographic measurements helped to construct a subject-specific knee model used to estimate the knee joint forces and the knee joint moments. Segmental inertial properties were estimated using regression equations based on subject specific anthropometrics (Clauser et al., 1969). The knee was modeled as a two-dimensional structure that could be positioned in three-dimensional space. The net three-dimensional forces and moments at the knee that were used in the analysis were defined by the following equations:

Table 1
Subject anthropometrics

Subject group	N	Age (years) ^a	Height (m) ^{b,c}	Weight (kg) ^{b,c}	BMI (kg/m ²) ^c
Normal subjects	63	46–80; avg. 65	1.68 (.09)	80.68 (15.4)	29.32
Knee OA patients	50	53–84; avg. 70	1.63 (.09)	86.63 (22.1)	28.81

^a The age of the subjects is given in the form of a range and average.

^b The average height and weight are given, as well as their standard deviations.

^c No significant difference.

$$\vec{F}_K = \vec{F}_Q + \vec{F}_H + \vec{F}_C$$

$$\vec{M}_K = \vec{F}_Q \times \vec{r}_Q + \vec{F}_H \times \vec{r}_H$$

where:

- \vec{F}_K three-dimensional net force at the knee joint
- \vec{F}_Q force produced by the quadriceps muscles
- \vec{F}_H force produced by the hamstrings muscles
- \vec{F}_C knee joint contact force
- \vec{M}_K three-dimensional net moment at the knee joint
- \vec{r}_Q the moment arm of the quadriceps muscles
- \vec{r}_H the moment arm of the hamstrings muscles.

In this model, it was assumed that the forces produced by the quadriceps and hamstrings muscles, \vec{F}_Q and \vec{F}_H , act solely in the lateral–medial direction. The sagittal plane moment and the quadriceps or hamstring moment arm were used to estimate the muscle force required to generate the net knee flexion moment. The model assumed no co-contraction of the quadriceps and hamstrings muscles. Knee extension was produced solely to the quadriceps muscles, and knee flexion was produced solely by the hamstrings muscles. The assumption of no co-contraction underestimates the magnitude of the joint contact forces at the knee. Contributions from other muscles (such as the gastrocnemius muscles) and soft tissues were ignored by the model. It was also assumed that the muscle moment arms were considered constant. The muscle force was computed by dividing

the net moment by the appropriate moment arm and estimating the orientation of the muscle force vector. The net joint knee forces in the posterior–anterior and distal–proximal directions are equal to the joint contact forces in these directions because it was assumed that the quadriceps and hamstrings muscles acted only in the lateral–medial direction.

2.2. Analysis

Nine *waveform measures* and eight *discrete measures* were analysed simultaneously in this study (Table 2). *Waveform measures* are dynamic gait measurements that vary continuously in time throughout gait. To compare the waveforms of subjects with varying stride times, the waveform measures are time normalized to represent one complete gait cycle. Each waveform is defined by 101 values, one for each percent of the gait cycle. *Discrete measures* are specified by a single value and include both stride characteristics and parameters that are related to knee osteoarthritis, such as the radiographic hip knee ankle angle in the frontal plane. A complete list of the parameters is provided in Table 2.

The original variables were standardized to have a zero mean and unit variance to account for differences in the relative magnitudes and units of the measures (Johnson and Wichern, 1998). All 113 subject observations on the standardized original variables were contained in the (113 × 917) analysis matrix, X :

$$X = [X_{aPA} \ X_{aLM} \ X_{aDP} \ X_{mPA} \ X_{mLM} \ X_{mDP} \ X_{fPA} \ X_{fLM} \ X_{fDP} \ X_d]$$

where X is partitioned into 10 matrices. The first nine partitions of X represent the *waveform measures*; X_d contains the eight *discrete measures* (Table 2).

The major features of variation in the data were extracted using principal component analysis (PCA), a multivariate statistical analysis technique. With PCA, the standardized variables were orthogonally rotated into new, uncorrelated variables called features, which maximally explained the variability in the original

Table 2
The 17 input measures considered in the multidimensional analysis

Analysis input measures			Discrete measures		
Symbol	Description	Units	Symbol	Description	Units
a_{PA}	Knee ab/adduction angle	deg	c_1	Stride length	s
a_{LM}	Knee flexion/extension angle	deg	c_2	Velocity	m/s
a_{DP}	Knee internal/external rotation angle	deg	c_3	Stance percentage	(%)
m_{PA}	Ab/adduction moment	Nm/kg	c_4	Stance time	s
m_{LM}	Flexion/extension moment	Nm/kg	c_5	Hip knee ankle (HKA) angle	deg
m_{DP}	Internal/external rotation moment	Nm/kg	c_6	Standing knee flexion angle	deg
f_{PA}	Posterior–anterior knee force	N/kg	c_7	Medial joint space	mm
f_{LM}	Lateral–medial knee force	N/kg	c_8	Body mass index (BMI)	(kg/m ²)
f_{DP}	Distal–proximal knee force	N/kg			

variables. The dimension of the data can be reduced with PCA because the majority of information in the data is generally captured by a small subset of the first extracted features (Jackson, 1991). A subset of features that cumulatively explained at least 90% of the original data variation was retained for further analysis (Jackson, 1991). The orthogonal projection of an original observation onto a feature was referred to as a principal component score (PC score). Subject data were reduced from the original 917 variables to a reduced set of PC scores, contained in the matrix \mathbf{Z} :

$$\mathbf{Z} = \mathbf{X} \times \mathbf{U}_r = \mathbf{X} \times [\vec{u}_1 \dots \vec{u}_r] = [\vec{z}_1 \dots \vec{z}_r] \quad (1)$$

where:

- \mathbf{Z} (113 × r) matrix of PC scores for each subject on all retained features
- r the number of retained features ($r \ll 917$)
- \mathbf{X} the (113 × 917) matrix of original standardized variables
- \mathbf{U}_r the (917 × r) matrix of the first k eigenvectors of the covariance matrix of \mathbf{X}
- \vec{u}_i the vector containing the i th eigenvector (feature i)
- \vec{z}_i the (113 × 1) vector of the PC score observations on feature i , for each subject.

A backwards elimination stepwise discrimination procedure was employed to determine the subset of retained features that optimally separated the normal and OA groups of PC scores (Lachenbruch, 1975). The magnitude of a feature's coefficient in the discriminant function quantified the relative importance of the feature in the multivariate separation of the two groups (Johnson and Wichern, 1998).

Because principal component analysis and linear discriminant analysis are linear transformation techniques, biomechanical interpretation of the features was possible through interrogation of the underlying structure of the models. For example, relative magnitudes of feature coefficients in the linear discriminant function can be compared to establish the relative importance of each feature to group separation. To investigate the biomechanical significance of the discriminatory features, the features were interpreted in terms of (i) the relative contributions of the input *waveform measures* and the *discrete measures*, and (ii) the relative importance of each portion of the gait cycle.

The relative importance of an original variable within a feature was quantified by the correlation between the variable and the feature, or *percent variation explained*. *Percent variation explained* represents the amount of variation in the original variable explained by a feature.

$$\text{Percent variation explained}(i, j) = \frac{100u_{ij}\sqrt{\text{var}(\vec{z}_i)}}{\text{var}(\vec{x}_j)}$$

where *Percent variation explained*(i, j) is the percent variation explained of the original variable, \vec{x}_j ,

- u_{ij} the coefficient of \vec{x}_j in feature i
- \vec{z}_i the vector of PC scores for all subjects, corresponding to feature i
- $\text{var}(\vec{z}_i)$ the variance of feature i
- \vec{x}_j the vector containing all observations on the j th original standardized variable
- $\text{var}(\vec{x}_j)$ the variance of \vec{x}_j
- $\text{var}(x_j)$ the variance of x_j .

An average *percent variation explained* value over the gait cycle was used to represent the contribution of a *waveform measure*. To quantify the overall relative importance of each percentage of the gait cycle to a feature, an average *percent variation explained* value was calculated over the nine *waveform measures*, at each percent of the gait cycle. Each feature represented a different linear combination of the original gait variables. By comparing the magnitudes of the coefficients, we could quantify the relative contributions of each original gait measure and each percentage of the gait cycle to the features.

The discriminant function was defined as a linear combination of principal components, which were linear combinations of the original variables. The discriminant function could therefore be represented as a linear combination of the original variables. The sign of the coefficient of an original variable in the discriminant function indicated how the variable contributed to group separation. An original variable with a large positive coefficient in the discriminant function contributed to a large discriminant score, and was associated with the normal gait pattern group. A large negative coefficient was associated with the OA gait pattern group.

3. Results

Twenty-five features extracted with principal component analysis explained greater than 90% of the variation in the data and were retained for further analysis. A backward elimination stepwise discriminant analysis indicated that twelve of the twenty-five features was an optimal set to separate the normal group of PC scores from the OA group of PC scores. A linear discriminant function, created with the twelve features chosen in the stepwise procedure, successfully separated the groups with a misclassification error rate of <6%, estimated through Lachenbruch's cross-validation technique (Lachenbruch, 1975) (Fig. 1).

A hierarchy of discriminatory power among the features was established by comparing the relative magnitudes of feature coefficients in the linear discriminant function (Lachenbruch, 1975). Feature 1, the first feature extracted with PCA, explained the largest percent-

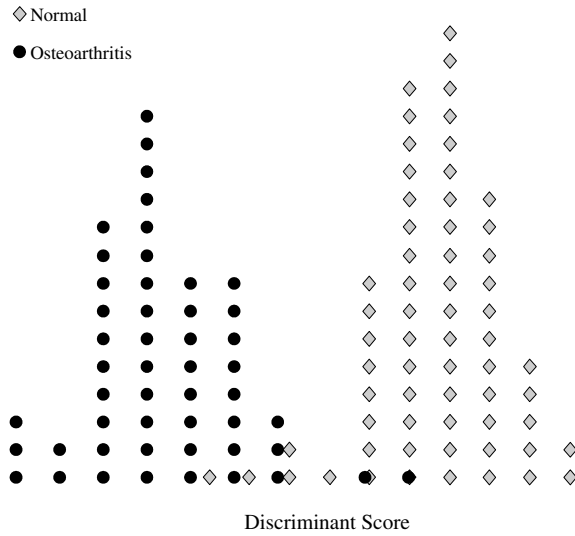


Fig. 1. *Discriminant scores.* The discriminant score histograms of 63 normal subjects (diamond) and 50 knee OA subjects (circle) are shown. The two groups of discriminant scores were well separated, with a cross-validation misclassification of 6%.

age of the original variation in the data, and had the largest coefficient in the linear discriminant function and was therefore the most discriminatory feature. Feature 1 had major contributions from both *waveform measures* and *discrete measures* related to frontal plane alignment. Contributing measures included the lateral–medial knee joint force, the knee adduction moment, stance time, the internal rotation moment at the knee, the static HKA angle in the frontal plane, velocity and the standing knee flexion angle (Fig. 2). The feature was most important from approximately twenty to sixty percent of the gait cycle, the latter portion of the stance phase of the gait cycle (Fig. 3). The most discriminatory feature was therefore biomechanically interpreted as a stance phase, frontal plane loading and alignment factor.

The discriminant function coefficients of the major contributors to feature 1 indicated how each of the major contributing measures contributed to group separation. The discriminant function coefficients of the discrete measures that contributed to feature 1 are shown in Fig. 4. The severe OA group was associated with larger stance times, smaller HKA angles (i.e. more varus), smaller velocities, and smaller standing flexion angles. During the portion of the gait cycle that is important to feature 1 (20–60%), the severe knee OA group was associated with smaller lateral–medial joint forces, larger adduction moments and larger than smaller internal rotation moments of the knee (Fig. 5). A biomechanical interpretation summary of feature 1 is provided in Table 3.

Interestingly, the second most discriminatory feature was the 20th feature extracted with principal component

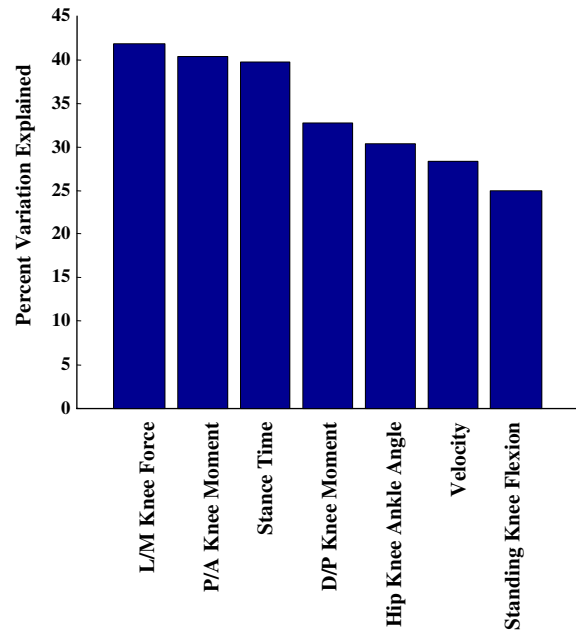


Fig. 2. *Major contributing measures to feature 1.* The percent variation explained values for the seven major contributors to feature 1 are shown. Each major contributor had a percent variation explained of at least 50% the maximum percent variation explained.

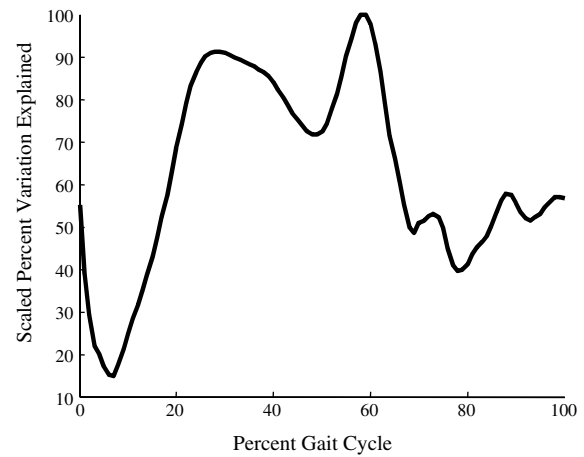


Fig. 3. *Gait cycle importance to feature 1.* An average of the percent variation explained values over the nine waveform gait measures was calculated at each percent of the gait cycle. Percent variation explained values were scaled to one hundred percent. Feature 1 was important during the stance phase of the gait cycle, from approximately 20–60% of the gait cycle.

analysis. Feature 20 captured approximately 1% of the original data variation, and was therefore a relatively low-variance, but very discriminatory feature. Body mass index, a relative obesity measure, was the major contributing measure to the feature (Fig. 6). Other important contributing factors included the lateral–medial bone-on-bone knee force, velocity, the flexion moment, the internal rotation angle, and the distal–proximal bone-on-bone knee force. The loading

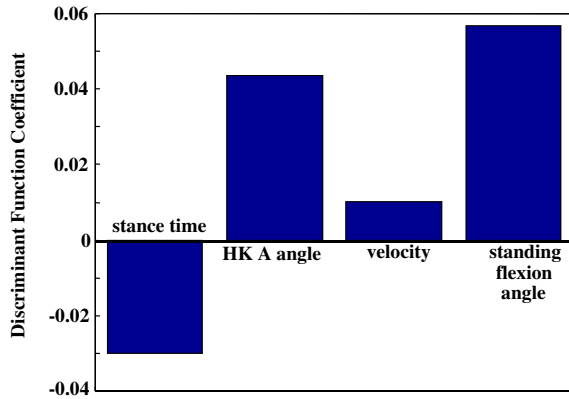


Fig. 4. Feature 1 discrete measure discriminant function coefficients. The discriminant function coefficients of major contributing discrete measures to feature 1 are shown. The osteoarthritis group was associated with large observations on measures with negative discriminant function coefficients (stance time), or by small observations on measures with positive coefficients (HKA angle, velocity, standing flexion angle).

response phase of the gait cycle (0–12%) was completely isolated as the important portion of the gait cycle to this discriminatory feature (Fig. 7).

The signs of the discriminant function coefficients of the contributing measures to feature 20 indicated that the OA group was associated with larger BMI parameters, smaller velocities, and changes in the waveform measures that are summarized in Table 4.

4. Discussion

Feature 1, the most discriminating principal component, represented a frontal plane loading and alignment factor associated with severe knee osteoarthritis during the stance phase of the gait cycle. It had major contributions from several alignment-related measures, including the dynamic knee adduction moment, the knee joint

Table 3
Biomechanical interpretation summary of feature 1

Major contributors		Normal group	OA group
Waveform measures	Portion of gait cycle		
Lateral–medial force	20–60%	Larger	Smaller
Adduction moment	20–60%	Smaller	Larger
Internal rotation moment	20–40%	Smaller	Larger
	40–60%	Larger	Smaller
Discrete measures			
Stance time		Smaller	Larger
HKA angle (+ values)		Larger	Smaller
Velocity		Larger	Smaller
Standing flexion angle		Larger	Smaller

force in the lateral–medial direction and the static hip knee ankle angle, or the frontal plane alignment angle. Previous gait studies have analysed these gait measures and have associated knee osteoarthritis gait patterns with larger stance phase adduction moments (Hurwitz et al., 2002; Kaufman et al., 2001) and more varus frontal plane alignment angles (Sharma et al., 2000; Teixeira and Olney, 1996; Olney et al., 1994). Positive correlations between these dynamic and static alignment measures have also been identified (Hurwitz et al., 2002; Andrews et al., 1996; Hilding et al., 1995; Olney et al., 1994). This result not only supported the importance of alignment to osteoarthritis, but it demonstrated the interaction between the measures and the particular portion of the gait cycle when alignment differences are important. Feature 1 points to an underlying mechanism that is expressed through differences in each of the individual alignment measures. It supports the interaction between alignment-related measures in the abnormal gait patterns of patients with severe knee osteoarthritis. Further, the difference has been isolated to the latter part of the stance phase of the gait cycle.

Feature 20, the second most discriminatory principal component, explained only a small percentage of the

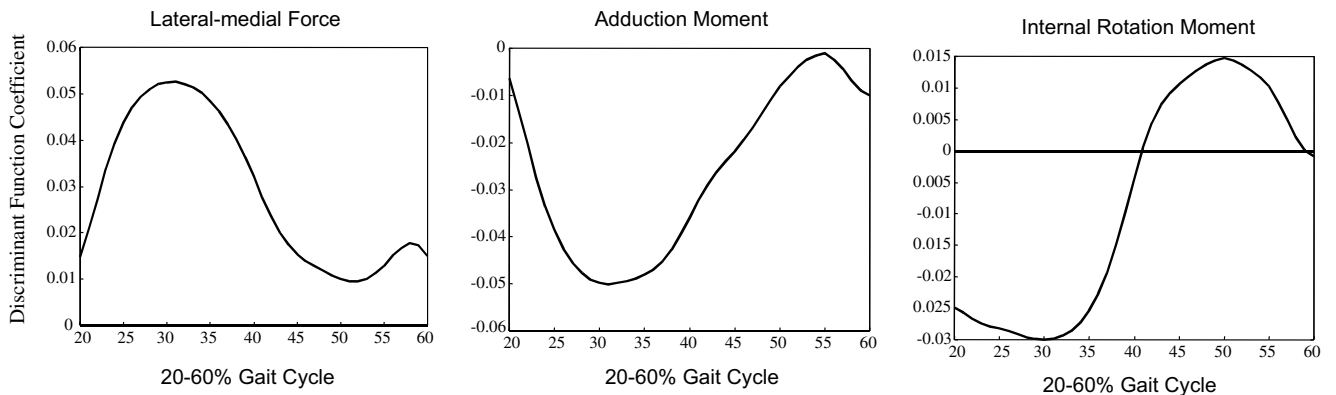


Fig. 5. Feature 1 waveform measure discriminant function coefficients. The discriminant function coefficients for the contributing waveform measures to feature 1 are shown for 20–60% of the gait cycle, the portion of the gait cycle that is important to feature 1 (Fig. 3). Small lateral–medial knee joint forces, large adduction moments and initially larger, then smaller internal rotation moments are associated with the severe knee OA group.

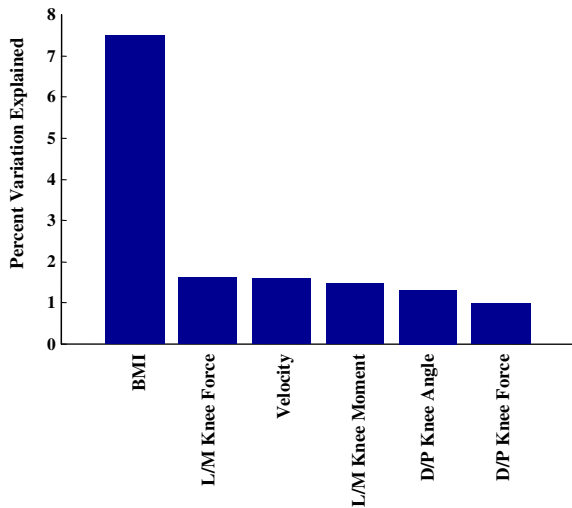


Fig. 6. Major contributing measures to feature 20. BMI was the major contributing measure to feature 20, the second most discriminatory feature.

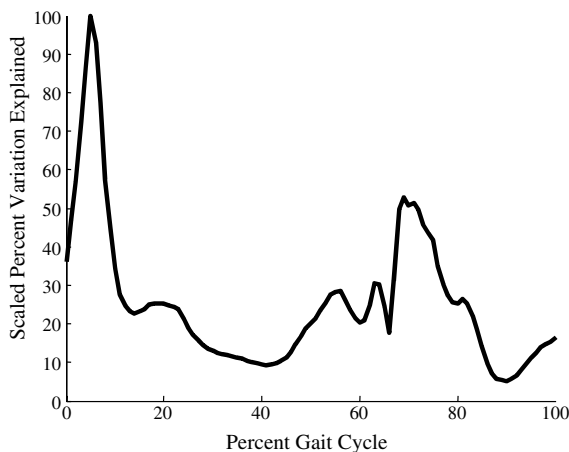


Fig. 7. Gait cycle importance to feature 20. An average of the percent variation explained values over the nine waveform gait measures was calculated at each percent of the gait cycle. Percent variation explained values were scaled to one hundred percent. Feature 20 was important during the initial portion of the gait cycle, known as the loading response phase.

Table 4
Biomechanical interpretation summary of feature 20

Major contributors	Normal group	OA group
<i>Waveform measures</i>		
Lateral–medial force	Larger	Smaller
Flexion moment	Larger	Smaller
Internal rotation angle	Smaller	Larger
Distal–proximal force	Larger	Smaller
<i>Discrete measures</i>		
BMI	Smaller	Larger
Velocity	Larger	Smaller

variation in the data, but what it did explain was very discriminatory information. Statistical literature has rec-

ognized the potential discriminatory power of small variance features extracted with principal component analysis (Jolliffe, 1982; Hawkins and Fatti, 1984). This feature involved a combination of differences in several measures, with the greatest contribution from BMI, a relative obesity measure. The fact that there was no statistically significant difference between the normal and severe knee OA BMI values highlighted the multidimensionality of the changes that occur with knee osteoarthritis. Feature 20 is a multidimensional feature of gait patterns. The difference described by feature 20 cannot be contributed to a single gait measure. While BMI was not important as a single parameter, it was very important in combination with the other gait differences that contributed to feature 20. Obesity has been previously identified as a characteristic of osteoarthritis patients that has the potential to alter knee joint mechanics (Fisher and Pendergast, 1997). These results support that obesity is important to knee osteoarthritis, but suggest that its importance lies in combination with other concurrent changes in joint mechanics during the loading response phase of the gait cycle.

Another interesting interpretation result of feature 20 was that it completely isolated the loading response phase of the gait cycle. Loading response is the initial part of the gait cycle that immediately follows heel strike, when a subject is shifting their body mass from a double-limbed stance to a single supporting limb (Perry, 1992). Loading response represents one of the most demanding tasks during gait, requiring a great deal of coordination, shock absorbency and limb stability (Perry, 1992), all of which can be compromised with knee osteoarthritis. The isolation of loading response in a very discriminatory feature suggests that there are important gait pattern differences just after heel strike in patients with severe osteoarthritis of the knee.

The net reaction forces at the knee were not predominant in the model. The knee model used in this analysis was a very conservative model that underestimates the net reaction forces at the knee. A more in-depth model may reveal more importance of the knee joint forces.

In the creation of the multidimensional gait data analysis technique, it was desirable to compare patients on either end of the knee osteoarthritis disease spectrum, severe knee OA patients and normal subjects, where definite differences were expected. The technique can now be generalized to apply to populations with less severe forms of the OA disease process. While the technique identified the importance of the loading response phase of the gait cycle to end-stage knee osteoarthritis, further investigation of the gait patterns of patients at earlier stages of the disease process would be necessary to determine if the feature is important to disease propagation. The importance of the loading response phase of the gait cycle to knee osteoarthritis has been speculated in previous analyses. Radin et al. (1991) identified an

impulsive foot-ground reaction at heel strike in a group of subjects with mild, activity-related knee pain, presumably consistent with pre-osteoarthritis. This rapidly applied loading was speculated to be provoking joint damage and creating osteoarthritic changes within the knee. Quantifying a similar gait pattern difference at heel strike in a population with end-stage knee osteoarthritis suggests that the difference may be important to the propagation of knee OA, and warrants further investigation.

5. Conclusions

The results of this study emphasized the need for multivariate gait data analysis techniques. Exploiting the interrelationships between multiple measures in the analysis of gait data can provide important insight into knee osteoarthritis gait patterns. Features were identified that incorporate differences in multiple dynamic and discrete gait measures. The results demonstrated the potential for including both time varying measures and discrete parameters simultaneously in the analysis of gait data.

Extracting clinically important information from gait data is a huge problem faced in gait analysis. Results are commonly interpreted subjectively from a large number of highly correlated, time-varying and constant variables. The multidimensional technique that was used in this study to detect biomechanical differences with knee osteoarthritis represented an objective method of simultaneously reducing and analysing many interrelated time varying and discrete gait measures.

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