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Reliability of Principal Components and Discrete Parameters of Knee Angle and Moment Gait Waveforms in Individuals with Moderate Knee Osteoarthritis

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Abstract

Gait measures are used to evaluate change in patients with knee osteoarthritis (OA), but reliability has not been fully established in this population. This study examined test-retest reliability of knee angle and moment gait waveform characteristics captured using discrete parameters and principal component analysis (PCA) in individuals with moderate knee OA. Participants (n=20) underwent three-dimensional gait analysis on two occasions. Motion and force data were captured using two camera banks, infrared light emitting diodes and force plate during self-selected walking. Knee angle and moment waveforms were calculated and analyzed using discrete parameters and by identifying waveform characteristics using PCA. Intraclass correlation coefficients ($ICC_{2,k}$) examined test-retest reliability of discrete parameters and PCA derived scores (*PC-scores*). $ICC_{2,k}$ values ranged from 0.57-0.93 for discrete parameters, 0.52-0.86 for knee angle *PC-scores* and 0.30-0.94 for the knee moment *PC-scores*. However, 10 of 13 discrete parameters, 6 of 9 knee angle *PC-scores* and 7 of 9 knee moment *PC-scores* had $ICC_{2,k}$ values greater than or equal to 0.70. Discrete parameters and *PC-scores* from flexion angles and adduction moments had the highest $ICC_{2,k}$ values while adduction angles, rotation angles, and rotation moments had the lowest. Most knee angle and moment waveform characteristics demonstrated $ICC_{2,k}$ values that could be interpreted as acceptable. Caution should be used when examining adduction and rotation angle magnitudes and early/mid-stance rotation moment magnitudes due to lower $ICC_{2,k}$ values.

Key words: knee osteoarthritis, gait, biomechanics, reliability, principal component analysis

Introduction

Knee osteoarthritis (OA) is a prevalent condition affecting over 11.5% of adults worldwide [1]. To gain a better understanding of this disease and its management, it is important to examine longitudinal change and evaluate interventions in this population. This requires reliable outcome metrics. Three-dimensional gait analysis is a measurement tool that has examined longitudinal change [2], investigated changes with disease severity [3], and evaluated treatments in knee OA samples [4]. However, reliability of gait variables has not been fully established in this population [5].

Gait studies of healthy participants found intraclass correlation coefficients (ICC) between 0.61 to 0.97 for discrete waveform parameters including knee adduction moment impulse, peak toe-out angle and peak knee moments [6-8]. Furthermore, reliability has been investigated by comparing variability of entire waveforms between testing sessions using the coefficient of multiple correlation [9-11]. Generally, knee flexion angles in healthy adults during gait were more reliable than adduction and rotation angles. Flexion, adduction, and rotation knee moments demonstrated good reliability between sessions. Results varied between studies, likely due to discrepancies in marker locations and methods used for calculating angles and moments [9-11]. A few studies have reported ICC values greater than 0.69 for participants with knee OA for some discrete waveform values (e.g. peak knee adduction moment),[12,13] but a comprehensive investigation of three-dimensional knee angle and moment waveforms has not been reported in this population.

Numerous factors influence reliability of biomechanical data including selection of discrete parameters, location of markers, method of calculating joint angles and moments, and data collection systems and procedures [7,9,11]. Most knee OA gait reliability studies have investigated discrete parameters. More recently researchers have begun to use alternative waveform analysis techniques, such as principal component analysis (PCA), to capture temporal information and objectively reduce dimensionality of waveform data while retaining waveform pattern structure [14]. Differences in knee angle and moment waveforms have been found between healthy and knee OA groups and between different knee OA severities using PCA [3,15,16]. Despite the growing use of PCA in OA gait studies, the reliability of waveform features obtained using this technique has not been explored. The objective was to examine test-retest reliability of three-dimensional knee joint angle and moment waveform characteristics captured using PCA and discrete parameters in individuals with moderate medial compartment knee OA.

Participants

Participants (n=149) diagnosed with moderate knee OA by an orthopaedic surgeon (W.S.) using clinical and radiographic criteria [17] were recruited between May 2003 and October 2011 (Table 1). Participants were classified as moderate severity based on self-reported functional status including the ability to walk a city block, jog 5 m, and climb stairs in a reciprocal fashion [18]. This large group was used to generate stable waveform patterns using PCA (PCA group). Between 2010 and 2011, a subset of 22 participants (reliability group) underwent testing on two visits. Participants were included if they were over 35 years of age. Exclusion criteria included lower extremity surgery or trauma within the last year, previous lower extremity joint replacement or current candidate for replacement, other forms of arthritis, and history of neurological disease. The most symptomatic knee was chosen as the study leg in participants with bilateral knee OA. Standard anterior-posterior and lateral radiographs were acquired for the reliability group and scored by a single experienced (W.S.) reader using Kellgren-Lawrence radiographic grading [19]. The study was approved by the institutional research ethics board and informed consent was obtained from participants.

Methods

Data Collection

At each data collection, participants completed the Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) 3.1 Likert version [20] and height and mass were recorded.

Standard procedures were used for all gait analyses [15]. Infrared light emitting diode triads were placed on the sacrum, thigh, shank and foot of the study leg. Single markers were placed on the shoulder, greater trochanter, and lateral malleolus. Virtual markers identified during quiet standing included right and left anterior superior iliac spine, femoral medial epicondyle, tibia tubercle, fibular head, medial malleolus, head of the second metatarsal, and heel. The femoral lateral epicondyle was identified with either a single or virtual marker. For the reliability group, marker placements and digitization trials were completed by three investigators (S.R., D.R., G.H.). They performed the collections based on their availability and the same investigator did not necessarily complete both participant visits.

Participants completed two warm-up trials and then walked along a 5 m walkway at self-selected speeds for five to seven trials. Gait speed was monitored using infrared light timing gates to ensure that trials did not vary by more than 10%. Participants wore their own comfortable footwear and the reliability group wore the same footwear during both visits.

Lower limb three-dimensional motion was sampled at 100Hz with an Optotrak^{TM} 3020 optoelectronic motion capture system (Northern Digital Inc., Waterloo, Canada). Three-dimensional ground reaction forces and moments were sampled at 2000Hz (16 bit, +/-2 V), from a single force platform (Advanced Mechanical Technology Inc., Watertown, MA), embedded in the walkway, aligned with the global coordinates of the motion capture system, and synchronized with the motion capture data.

Data Processing

Data processing was completed using custom software written in Matlab 7.4 (Mathworks, Natick, MA). Positional marker and force plate data were low-pass filtered with 4th order Butterworth filters at 8 and 60 Hz respectively. Knee joint angles were calculated using previously described joint and anatomical coordinate systems [15,21]. Inverse dynamics equations calculated net external knee joint moments using measured marker and force plate data, with previously published segment inertial properties [22]. Moments were described about joint coordinate system axes. All angle and moment waveforms were time normalized to 100% gait cycle and moments were amplitude normalized to body mass. An ensemble average was created from five to seven gait trials for each angle or moment for each visit.

Analysis

Discrete gait parameters were extracted from ensemble waveforms for the reliability group. Parameter selection was based on previous studies [12,13,23] and described in Table 2 and Figure 1.

Principal Component Analysis

PCA was applied to each three-dimensional knee angle and moment waveforms (six analyses). PCA group waveforms (n=149) were included in the PCA model. PCA group contained participants who were tested once (n=127) and participants in the reliability group for one visit (n=22). For each angle or moment, data were arranged into a 149x101 matrix $\boldsymbol{X}$ (n=149 participants; 101=data points over 100% of gait). Principal components (PC) were extracted as eigenvectors ($\boldsymbol{U}$) from the covariance matrix of $\boldsymbol{X}$. PCs represented characteristics of the waveforms that maximally explained variability in the original data [14]. Corresponding eigenvalues indicated the amount of variability explained by each PC. For each measure, the first three PCs (PC1, PC2, PC3) were examined because these cumulatively represent the majority (>80%) of variability in the data and are typically reported in gait literature [3]. *PC-scores* were calculated for reliability group participants by projecting their waveform data with the group mean ($\bar{\boldsymbol{X}}$) removed onto each PC ($\textit{PC-scores}=(\boldsymbol{X}-\bar{\boldsymbol{X}})*\boldsymbol{U}$). *PC-scores* describe how closely the participant’s waveform matches the shape of PC. For reliability group participants, a *PC-score* for each PC (3; *PC1-score, PC2-score, PC3-score*) of each angle or moment (6) was calculated for both visits (2) (36 *PC-scores* total per participant).

To determine if PCA captured salient features of waveforms from the reliability group, waveforms were reconstructed from PC1 to PC3 ($\boldsymbol{X}_{recon}=\textit{PC-scores}*\boldsymbol{U}'+\bar{\boldsymbol{X}}$). Reconstructed waveforms ($\boldsymbol{X}_{recon}$) were compared to the original waveforms ($\boldsymbol{X}$) using a Q-statistic and Q-critical values were also determined [24]. Three PCs and corresponding *PC-scores* accurately captured original waveform features when the Q-statistic for a participant was less than the Q-critical value [24]. The number of Q-statistic values less than the Q-critical value was determined.

Statistical Analysis

Paired t-tests (α=0.05) compared WOMAC and gait speed between visits for the reliability group to ensure clinical status remained stable. Test-retest reliability of discrete parameters and *PC-scores* was examined using intraclass correlation coefficients (2,k) ($ICC_{2,k}$) with 95% confidence intervals (CI) and standard error of the measurements (SEM) with 95% CI [25,26]. Statistical analyses were completed using SPSS 17.0 (SPSS Inc., Chicago, IL).

Results

Data from two reliability group participants could not be used due to collection errors on one visit (n=20). Acceptable data from their other visit was still used in the PCA group. Table 1 provides characteristics for PCA (n=149) and reliability (n=20) groups including both visits for the reliability groups. Participants from the reliability group had Kellgren-Lawrence radiographic OA severity grades of I (n=4), II (n=7), III (n=5), and IV (n=3). One participant's radiographs were not available. Mean time between testing visits for the reliability group was 5.4 (2.7) weeks. No significant differences existed between visits for pain (p=0.31), stiffness (p=0.46), and physical function (p=0.24) WOMAC subscales and gait speed (p=0.12) (Table 1). Thus, clinical status remained consistent between visits. Figure 1 provides mean knee angle and moment waveforms for both testing visits (Supplemental 1 to 6 provides individual waveforms for reliability group participants).

Discrete Parameter Reliability

$ICC_{2,k}$ values were greater than 0.70 for 10 of 13 discrete parameters (Table 2). Flexion angle discrete parameters produced the highest $ICC_{2,k}$ values of the knee angles ($ICC_{2,k}=0.74$ to 0.90). Although adduction angle stance maximum had the lowest SEM value ($SEM=1.98^{o}$) (Table 2), it had one of the lowest $ICC_{2,k}$ values ($ICC_{2,k}=0.60$).

Adduction moment discrete parameters had the highest $ICC_{2,k}$ values of the knee moments ($ICC_{2,k}>0.90$). Internal rotation moment stance maximum had the lowest SEM value (SEM=0.03 Nm/kg). Flexion moment stance maximum had the lowest $ICC_{2,k}$ value ($ICC_{2,k}=0.57$).

Principal Component Score Reliability

PC descriptions are provided in Table 3 (Supplemental 7 to 12 provides PC graphs). PC1 to PC3 cumulatively captured 81 to 90% of the explained variance in angle and moment waveforms for the PCA group (Table 4). Comparing Q-statistic and Q-critical values, 17/20 to 20/20 of individual reconstructed and original waveforms were not significantly different in the reliability group indicating these three PCs accurately captured salient features of the original waveforms (Table 4).

Six of nine knee angle *PC-scores* produced $ICC_{2,k}$ values greater than 0.70 (Table 4). Flexion angle *PC-scores* produced the highest $ICC_{2,k}$ values for the knee angles ($ICC_{2,k}=0.84$ to 0.86). Knee adduction and rotation angle PC1, capturing overall magnitude of these angles, demonstrated the lowest $ICC_{2,k}$ values for knee angle *PC-scores* ($ICC_{2,k}=0.52$ to 0.54). However, other pattern characteristics (adduction angle PC2 and PC3, rotation angle PC2) of these angles during stance had greater $ICC_{2,k}$ values ($ICC_{2,k}$=0.74 to 0.79).

Seven of nine knee moment *PC-scores* produced $ICC_{2,k}$ values greater than or equal to 0.70 (Table 4). Adduction moment *PC-scores* produced the highest $ICC_{2,k}$ values for the knee moments ($ICC_{2,k}$>0.90). Rotation moment *PC2-scores* and *PC3-scores* had the lowest $ICC_{2,k}$ values ($ICC_{2,k}$=0.50 and 0.30 respectively); however, the overall magnitude of the rotation moment during mid/late stance (*PC1-score*) produced higher $ICC_{2,k}$ values ($ICC_{2,k}$=0.84).

Discussion

The majority of knee angle and moment waveform characteristics captured using discrete parameters and PCA had $ICC_{2,k}$ values greater than 0.70 that support acceptable test-retest reliability in participants with moderate knee OA. Hence, most discrete parameters and *PC-scores* can examine changes in gait longitudinally, including treatment response, in individuals with knee OA. Some *PC-scores* and discrete parameters demonstrated lower $ICC_{2,k}$ values (<0.70) and therefore more questionable test-retest reliability. These variables were associated with adduction and internal rotation angle overall magnitudes and internal rotation moment magnitude from early to mid-stance. These scores should be interpreted cautiously when comparing between visits [27].

Reliability can be influenced by raters, measuring instrument and research participants [28]. Concerning raters, the same investigator did not necessarily apply markers on both visits and error might have resulted from changes in marker location. Investigators received standardized training and a standardized protocol, including consistent marker placement, instrumentation and data processing techniques, limited variability between visits. Symptom fluctuations could decrease gait measure reliability in participants with knee OA making them less reliable compared to healthy participants. Current participants had no significant change in their symptoms (WOMAC subscales) and large fluctuation unlikely occurred. Regardless, a standardized protocol using different raters in a population with the potential for symptom fluctuations produced $ICC_{2,k}$ values greater 0.70 for the majority of knee angle and moment waveform characteristics.

Test-Retest Reliability

This study is the first to provide comprehensive examination of test-retest reliability of three-dimensional knee angle and moment parameters in participants with knee OA. In comparison to previous studies of healthy and knee OA samples, $ICC_{2,k}$ values for discrete parameters from knee angle and moment waveforms were similar, however our values for adduction angles were lower [7,8,12]. Discrete parameters and *PC-scores* from knee flexion angles were more reliable than adduction and internal rotation angles consistent with healthy participants [9-11]. Generally, adduction and rotation angle *PC-scores* that were difference operators, describing changes in range of motion or examined angle magnitudes during specific gait phases (*PC2*- and *PC3-scores*), were more reliable than measures of overall magnitude throughout gait (*PC1-scores* or discrete parameters). Reliability for adduction and rotation angles can be influenced by kinematic cross-talk, in particular at greater flexion angles. Inaccuracies in flexion/extension axis alignment result in errors in these angles [27]. Changes in marker placement between visits contribute to these inaccuracies which is pertinent in participants with knee OA because they have increased body mass compared to healthy participants [3] making it more difficult to identify and track boney landmarks. This affects overall magnitude (PC1 scores) of adduction and rotation angles more so than the difference operators. Thus, the latter assessment of ranges of motion provides more stable measures whereas caution should be used when interpreting overall knee adduction and internal rotation angles.

Discrete parameters and *PC-scores* from knee adduction moments followed by flexion moments had the highest $ICC_{2,k}$ values which is similar to studies of healthy individuals [9-11]. For the flexion moment, measures of overall magnitude (flexion moment stance maximum and *PC1-scores*) had lower $ICC_{2,k}$ values than difference operator (*PC2-scores*) and timing characteristics (*PC3-scores*). Similar to a previous study of healthy individuals [7], flexion moment stance maximum demonstrated the lowest $ICC_{2,k}$ value. The reason for this was not clear, but further data examination revealed that high values on one visit were not necessarily repeated on the other visit. Regardless, the majority of knee moment features captured with discrete parameters and *PC-scores* demonstrated $ICC_{2,k}$ values greater than 0.70 in participants with knee OA.

Comparison of Discrete Parameters and Principal Component Analysis

PC-scores had similar or slightly higher $ICC_{2,k}$ values than discrete parameters except for the knee rotation moment (Table 2 and 4). Most discrete parameters capture magnitude characteristics of waveforms such as maximum flexion angle during mid-stance or swing. Similarly, *PC1-score* captures overall magnitude of waveforms. For instance, flexion angle *PC1-score* had a similar $ICC_{2,k}$ value ($ICC_{2,k}$=0.84) as the maximum flexion angle during mid-stance and swing ($ICC_{2,k}$=0.77 and 0.94 respectively) and these waveform metrics captured similar characteristics (i.e. flexion angle magnitude). Thus, *PC-scores* and discrete parameters generally had similar reliability if they captured comparable waveforms characteristics.

Disadvantages of discrete parameters exist. First, in isolation, discrete amplitude parameters cannot account for temporal relationships within waveforms. Second, discrete parameters may not be identifiable in some waveforms or at an uncharacteristic time signature [14,29]. In this study, distinct late stance knee flexion angle minimums and late stance adduction moment peaks were not present in 13% and 23% of waveforms respectively corroborating previous work [29]. The advantages of PCA are that it considers waveform temporal information and objectively determines waveform features. However, this also presents potential limitations. Some PCs can be difficult to interpret since they are mathematical concepts and might not have apparent clinical significance. However, PC1 always represents waveform magnitude which is easily interpretable. PCs and *PC-scores* greatly depend on the group from which they are extracted and thus cannot be interpreted without comparing back to this group. Thus, it is not meaningful to calculate absolute reliability, quantified using SEM, or error in *PC-scores*.

SEM was used to augment ICC analysis, providing an indication of measurement error about discrete parameters. SEM magnitude comparison between parameters was difficult because SEM is influenced by the measure’s magnitude and variability. Furthermore, the current study does not have sufficient sample size to establish strong benchmarks for clinical change in individual patients for gait measures. Although the $ICC_{2,k}$ values appear acceptable and many could be classified as “good” based on qualifiers presented in the literature [28], differences in *PC-scores* existed between testing visits. This measurement error would need to be compared to the magnitude of changes that occur as result of disease progression, treatment, or gait modifying interventions to determine if the errors are of clinical importance. However, the results provide the first reliability data on a comprehensive set of biomechanical variables for the knee OA population. The qualitative waveform comparisons (Figure 1) are supported by the quantitative data and show that if there is no change in clinical status and presumably no change in disease progression (5 weeks between tests), then there are many biomechanical variables from discrete and PCA analyses that can be reliably measured using a standardized protocol. Secondly, they provide the foundation for future work to develop benchmarks for individual change based on larger samples that will yield more robust calculations of statistics such as minimal detectable change.

Limitations

Skin motion artefact cannot be ruled out and may have created an unknown effect on reliability estimates [30]. Time between visits for the reliability group was not consistent and varied between 2 to 11 weeks. However, clinical status remained stable over the study duration, which was demonstrated by no change in WOMAC scores. Three different investigators applied markers and the same investigator did not necessarily complete both participant visits. Using one investigator would have likely improved reliability estimates however this practice is not always feasible in treatment or long-term follow-up studies. Despite this, the majority of waveform characteristics had $ICC_{2,k}$ values greater than 0.70. High ICC values can be influenced by large between participant variance. The effect on current results does not necessarily support this as high ICC values were not always associated with greatest between participant variability (Table 2). The results were interpreted within the context of this limitation recognizing that the ICC can be used as an index of repeatability [28].

Summary

This study provided a comprehensive examination of test-retest reliability of three-dimensional knee angle and moment waveforms, based on discrete parameters and PCA, in individuals with knee OA. Discrete parameters and *PC-scores* derived from knee flexion angles, flexion moments and adduction moments generally demonstrated higher $ICC_{2,k}$ values indicative of acceptable test-retest reliability. In comparison, lower $ICC_{2,k}$ values for knee adduction and rotation angle magnitude measures and the early/mid-stance external rotation moment magnitudes suggest that change in these characteristics between visits should be interpreted cautiously. However, other characteristics of these waveforms demonstrated higher $ICC_{2,k}$ values that imply better test-retest reliability. Thus, the majority of knee angle and moment characteristics demonstrated acceptable test-retest reliability supporting their use in future studies to assess disease progression or response to treatment for those with knee OA.

Conflict of Interest Statement

The authors report no conflict of interest.

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Table 1: Means (standard deviations) for the group characteristics, gait speed and WOMAC subscales for both groups. Frequency count (percentage) for sex is provided.

Variable		PCA Group (n=149)	Reliability Group- Visit 1 (n=20)	Reliability Group- Visit 2 (n=20)
Age (y)		58 (9)	57 (9)	57 (9)
Sex Frequency	Women	54 (36)	7 (35)	7 (35)
	Men	95 (64)	13 (65)	13 (65)
Height (m)		1.72 (0.09)	1.73 (0.08)	1.73 (0.08)
Mass (kg)		91.0 (17.6)	94.6 (19.0)	94.5 (19.5)
BMI (kg/m^2)		30.6 (5.1)	31.4 (4.2)	31.5 (4.5)
Gait speed (m/s)		1.24 (0.19)	1.20 (0.18)	1.23 (0.16)
WOMAC-pain		7 (4)	7 (3)	7 (3)
WOMAC-stiffness		4 (2)	4 (1)	4 (2)
WOMAC-function		22 (12)	24 (10)	23 (10)
WOMAC-total		32 (16)	36 (14)	33 (13)

BMI=body mass index; WOMAC=Western Ontario McMaster Universities Osteoarthritis Index

Table 2: Descriptive and reliability statistics for the knee angles and net external moments discrete parameters.

Discrete Number*	Variable	Test Visit	Mean (SD)	ICC$_{2,k}$ (95% CI)	SEM (95% CI)
1	Flexion angle early/mid-stance (5-30% gait) maximum (^{o})	1	13.0 (6.4)	0.77 (0.41, 0.91)	3.73 (2.84, 5.45)
		2	12.4 (5.7)		
2	Flexion angle mid/late stance (30-62% gait) minimum (^{o})	1	5.4 (6.5)	0.74 (0.33, 0.90)	3.79 (2.88, 5.53)
		2	5.0 (5.1)		
3	Flexion angle swing (63-100%) maximum (^{o})	1	59.0 (8.0)	0.90 (0.75, 0.96)	3.17 (2.41, 4.63)
		2	59.7 (6.5)		
-	Flexion angle range (maximum-minimum) (^{o})	1	64.2 (7.3)	0.81 (0.14, 0.94)	3.39 (2.58, 4.96)
		2	68.8 (7.7)		
4	Adduction angle stance (0-62% gait) maximum (^{o})	1	3.8 (2.1)	0.60 (-0.02, 0.84)	1.98 (1.51, 2.90)
		2	4.3 (3.0)		
5	Internal rotation angle stance (0-62% gait) maximum (^{o})	1	8.7 (4.9)	0.68 (0.20, 0.87)	3.85 (2.93, 5.63)
		2	7.8 (6.1)		
6	Flexion moment early stance (0-15% gait) minimum (Nm/kg)	1	-0.26 (0.07)	0.81 (0.49, 0.93)	0.05 (0.04, 0.07)
		2	-0.30 (0.11)		
7	Flexion moment stance (0-62%) maximum (Nm/kg)	1	0.29 (0.18)	0.57 (-0.12, 0.83)	0.14 (0.11, 0.20)
		2	0.28 (0.18)		
8	Flexion moment mid/late stance (30-62% gait) minimum (Nm/kg)	1	-0.25 (0.22)	0.78 (0.47, 0.91)	0.11 (0.08, 0.16)
		2	-0.21 (0.16)		
9	Adduction moment early/mid stance (0-40% gait) maximum (Nm/kg)	1	0.51 (0.15)	0.91 (0.62, 0.97)	0.06 (0.04, 0.08)
		2	0.57 (0.18)		

10	Adduction moment late stance (40-62% gait) maximum (Nm/kg)	1	0.38 (0.13)	0.92 (0.80, 0.97)	0.06 (0.04, 0.08)
		2	0.39 (0.16)		
11	Adduction moment mid-stance (15-45% gait) minimum (Nm/kg)	1	0.29 (0.13)	0.93 (0.82, 0.97)	0.05 (0.04, 0.08)
		2	0.30 (0.16)		
12	Internal rotation moment stance (0-62% gait) maximum (Nm/kg)	1	0.16 (0.06)	0.88 (0.71, 0.95)	0.03 (0.02, 0.04)
		2	0.15 (0.08)		

SD=standard deviation; $ICC_{2,k}$=Intraclass correlation coefficients (2, k); CI=confidence intervals; SEM=standard error of the measurement

*Figure 1 provides graphical details of the discrete parameters with the numbers on Figure 1 matching this column.

Table 3: Description and explained variance captured by the principal components (PC) for knee angles and net external moments.

Variable	PC	Description	Variance Explained (%)
Flexion/ Extension Angle	1	Overall flexion angle magnitude over entire gait cycle.	53.6
	2	Timing of flexion angle during late stance/swing phase.	17.2
	3	Difference between flexion angle in early stance relative to swing phase.	10.8
Adduction/ Abduction Angle	1	Overall adduction angle magnitude over entire gait cycle.	71.8
	2	Adduction angle magnitude in early/mid-stance and late swing.	11.0
	3	Adduction angle magnitude in mid/late stance.	6.6
Internal/ External Rotation Angle	1	Overall internal rotation angle magnitude over entire gait cycle.	51.8
	2	Difference in internal rotation angle at early stance/late swing relative to late stance/early swing.	21.9
	3	Difference in internal rotation angle between late stance and early swing.	10.7
Flexion/ Extension Moment	1	Overall flexion moment magnitude in stance phase.	47.7
	2	Difference between peak flexion moment in early stance and peak extension moment in late stance.	38.1
	3	Timing of peak flexion moment in early stance and peak extension moment in late stance (phase shift).	4.6
Adduction/ Abduction Moment	1	Overall adduction moment magnitude in stance phase.	61.8
	2	Difference between early stance peak adduction moment relative to mid/late stance.	18.1
	3	Differences between mid-stance adduction moment relative to late stance peak moment.	6.2
Internal/ External Rotation Moment	1	Overall internal rotation moment magnitude in mid/late stance.	44.0
	2	External rotation moment magnitude in early/mid-stance.	40.5
	3	External rotation moment amplitude in early stance/loading response.	4.7

Table 4: The number of waveforms with a Q-statistic less than the Q-critical value and intraclass correlation coefficients ($ICC_{2,k}$) with 95% confidence intervals (CI) of the principal component scores (*PC-scores*) for the reliability group (n=20).

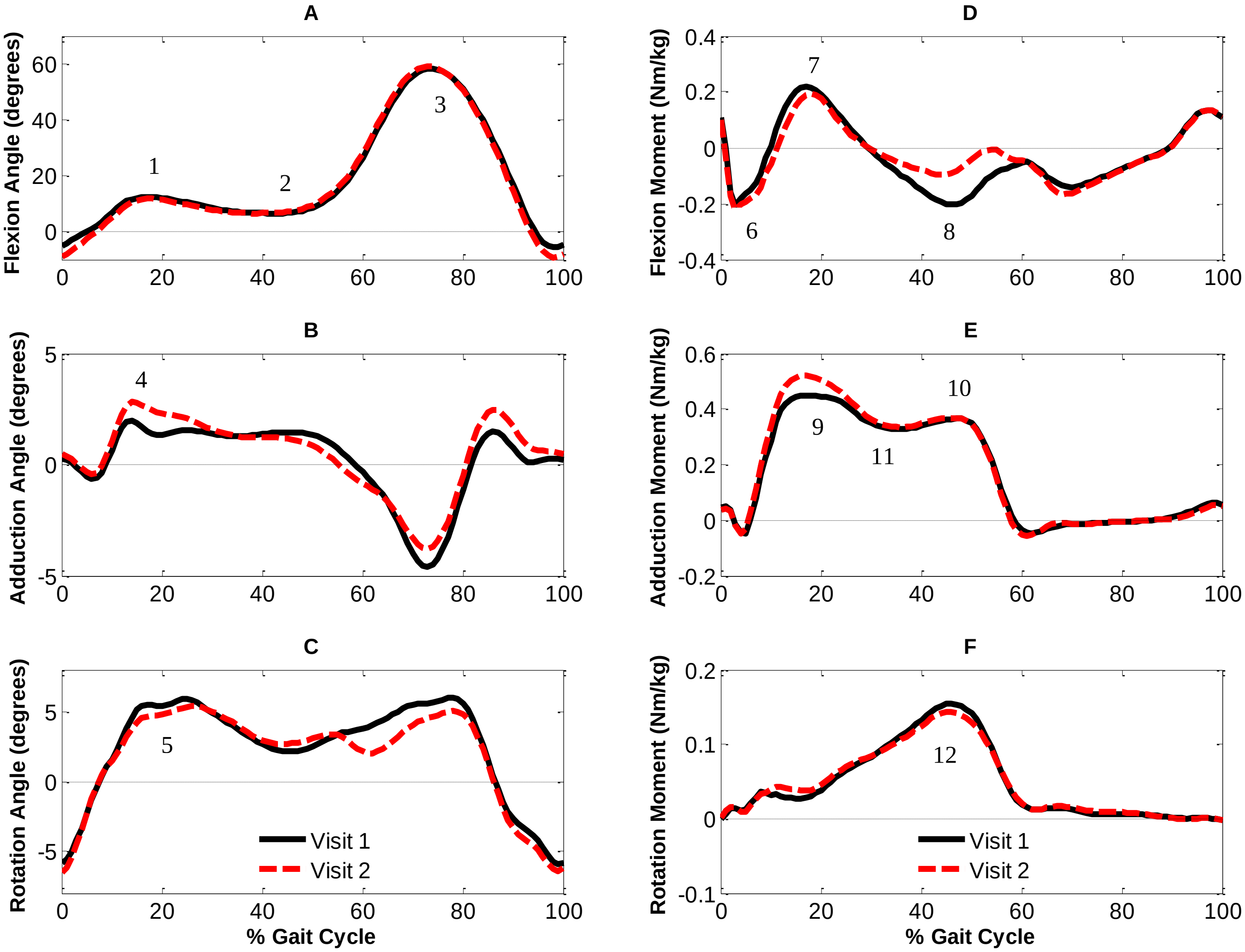
Variable	Q-statistic < Q-critical* Visit 1	Q-statistic < Q-critical* Visit 2	*PC-scores*	$ICC_{2,k}$	95% CI Lower	95% CI Upper
Flexion/Extension Angle	18/20	19/20	1	0.84	0.59	0.94
			2	0.86	0.65	0.94
			3	0.84	0.31	0.95
Adduction/Abduction Angle	19/20	19/20	1	0.52	-0.26	0.81
			2	0.76	0.42	0.91
			3	0.74	0.35	0.90
Internal/External Rotation Angle	19/20	20/20	1	0.54	-0.20	0.82
			2	0.79	0.46	0.92
			3	0.56	-0.11	0.83
Flexion/Extension Moment	19/20	20/20	1	0.70	0.25	0.88
			2	0.85	0.31	0.95
			3	0.92	0.79	0.97
Adduction/Abduction Moment	20/20	17/20	1	0.93	0.83	0.97
			2	0.94	0.66	0.98
			3	0.93	0.83	0.97
Internal/External Rotation Moment	19/20	18/20	1	0.84	0.60	0.94
			2	0.50	-0.28	0.81
			3	0.30	-0.86	0.73

*Represents the number of reconstructed waveforms that are not significantly different than the original waveforms.

Figure Caption

Figure 1. Knee angles (A-C) and external moments (D-F) during gait (0%=heel strike) for visit 1 (solid black line) and visit 2 (dashed read line) for the reliability group (n=20). Flexion, adduction and internal rotation represent positive values for the angles and moments. The numbers on the figures refer to the discrete parameters described in Table 2.

Figure1


A
Flexion Angle (degrees)
60
40
20
0
1
2
3
0
20
40
60
80
100
B
Adduction Angle (degrees)
5
0
-5
4
C
Rotation Angle (degrees)
5
0
-5
5
Visit 1
Visit 2
% Gait Cycle
D
Flexion Moment (Nm/kg)
0.4
0.2
0
-0.2
-0.4
6
7
8
E
Adduction Moment (Nm/kg)
0.6
0.4
0.2
0
-0.2
9
10
11
F
Rotation Moment (Nm/kg)
0.2
0.1
0
-0.1
12
Visit 1
Visit 2
% Gait Cycle

8. Supplementary Material

Research Highlights

We examined reliability of knee angles and moments in knee osteoarthritis patients.

Waveforms were examined using principal component analysis and discrete parameters.

Most principal component scores and discrete parameters had good reliability.

Some waveform features had fair reliability and should be interpreted cautiously.