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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 to 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, six of nine knee angle *PC-scores* and seven of nine 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.

1. 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 and 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.

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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.

2. 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.

3. Methods

3.1. 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., and 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 100 Hz with an Optotrak^{TM} 3020 optoelectronic motion capture system (Northern Digital Inc., Waterloo, Canada). Three-dimensional ground reaction forces and moments were sampled at 2000 Hz (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.

3.2. 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 Hz 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.

3.3. 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 Fig. 1.

3.4. 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 149×101 matrix $\mathbf{X}$ ($n = 149$ participants; 101 = data points over 100% of gait). Principal components (PC) were extracted as eigenvectors ($\mathbf{U}$) from the covariance matrix of $\mathbf{X}$. 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–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 ($\bar{X}$) removed onto each PC ($PC\text{-}scores = (X - \bar{X}) \times \boldsymbol{U}$). *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 ($\boldsymbol{X}_{recon} = PC\text{-}scores \times U' + \bar{X}$). Reconstructed waveforms ($\mathbf{X}_{recon}$) were compared to the original waveforms ($\mathbf{X}$) using a *Q*-statistic and *Q*-critical values were also

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.