

Classifying Pre-Radiographic Osteoarthritis of the Knee Using Wearable Acoustics Sensing at the Point of Care

Supplementary Material

Supplementary Table 1: Groupwise demographics of study participants

	Control	OA	Pre-OA
Subjects (N)	13	11	8
Age (Mean)	46.2	63.0	46.8
BMI (Mean)	28.9	32.0	35.9
Sex (M)	76.9%	63.6%	75.0%

Supplementary Table 2: Total number of knees evaluated, by group, and number of knees included for each scripted maneuver. Data from flexion-extension and sit-to-stand maneuvers were excluded from the dataset if movement cycles exceeded 0.40 Hz to lessen variation introduced by large biomechanical forces present in vigorous movement. No pace threshold was used for walking. If a participant was unable to complete a scripted maneuver or an error which occurred during acoustic measurement was identified after the participant's visit, only their data for the corrupted maneuver was excluded from the dataset to preserve as much data as possible.

	Control	OA	Pre-OA
Knees	20	12	11
- Flexion-Extension	18	12	11
- Sit-to-Stand	16	9	9
- Walking	20	10	10

Supplementary Table 3: Mean \pm standard deviation of Knee Injury and Osteoarthritis Score (KOOS) subscales for pre-OA and OA participants. Subscale scoring ranges from 0 to 100, with 100 representing healthy, unimpeded function and 0 representing the most severe injury and interference with daily function.

Group	KOOS: Pain	KOOS: Other Symptoms	KOOS: Function in Daily Living	KOOS: Function in Sport/Recreation	KOOS: Quality of Life	Presence of Crepitus
OA	47 \pm 10	45 \pm 9	55 \pm 12	24 \pm 7	22 \pm 16	100%
pre-OA	58 \pm 21	60 \pm 18	64 \pm 20	42 \pm 25	34 \pm 26	100%

Supplementary Table 4: Median values +/- standard deviation for individual scripted maneuvers included in our optimized classification models by scripted maneuver and group. After finding non-normal feature distributions with the Shapiro-Wilk Test, Kruskal-Wallis Test was used to compare feature medians between groups. Dunn's test was used for post-hoc analyses with the Bonferroni correction. Several acoustic feature means were different between healthy and pre-OA and healthy and OA for flexion-extension and sit-to-stand. Only healthy vs OA had significantly different median values for walking measurements. Significant p-values are bolded. Pre-OA: early pre-radiographic osteoarthritis; OA: radiographic osteoarthritis; MFCC: Mel-Frequency Cepstrum Coefficient; RMS: root-mean-square value.

Flexion-Extension

Acoustic Feature	Healthy Mean ± Std. Dev.	Pre-OA Mean ± Std. Dev.	OA Mean ± Std. Dev.	p: Kruskal-Wallis	p: Healthy - pre-OA	Healthy - pre-OA Effect Size	Healthy - pre-OA 95% CI	p: Healthy - OA	Healthy - OA Effect Size	Healthy - OA 95% CI	p: pre-OA - OA	pre-OA - OA Effect Size	pre-OA - OA 95% CI	Model
Spectral centroid	1331.228 ± 240.272	1066.751 ± 235.388	934.270 ± 169.968	0.000	0.014	1.0787	[0.921 23.17]	0.000	1.8003	[6.77 28.4]	0.417	0.6321	[-6.71 17.81]	Pre-OA
Spectral entropy	0.689 ± 0.047	0.648 ± 0.054	0.605 ± 0.038	0.000	0.045	0.8129	[-1.05 21.19]	0.000	1.8849	[8.03 29.68]	0.129	0.8896	[-3.47 21.04]	Pre-OA
Spectral Roll-Off Point	3882.395 ± 456.435	3239.930 ± 744.224	3241 ± 520.968	0.001	0.005	1.0853	[8.87 39.73]	0.002	1.2934	[13.33 43.39]	1.000	-0.0018	[-12.76 20.89]	Pre-OA
MFCC 1	2.842 ± 0.230	3.200 ± 0.371	3.179 ± 0.234	0.001	0.005	-1.2058	[-24.86 -2.61]	0.001	-1.4174	[-25.78 -4.12]	1.000	0.0657	[-13.47 11.04]	Pre-OA
MFCC 2	-1.422 ± 0.141	-1.356 ± 0.181	-1.152 ± 0.131	0.000	0.499	-0.4157	[-15.6 6.62]	0.000	-1.9273	[-28.34 -6.69]	0.017	-1.2623	[-25.27 -0.75]	OA
MFCC 6	-1.064 ± 0.073	-0.992 ± 0.072	-0.943 ± 0.053	0.000	0.045	-0.959	[-21.19 1.05]	0.000	-1.7873	[-28.40 -6.75]	0.214	-0.7614	[-19.76 4.75]	OA
MFCC 8	-0.704 ± 0.042	-0.644 ± 0.045	-0.616 ± 0.051	0.000	0.004	-1.3456	[-25.12 -2.86]	0.000	-1.8788	[-29.96 -8.30]	0.474	-0.5693	[-17.39 7.12]	OA
Band Power 825-870 Hz	0.045 ± 0.013	0.043 ± 0.011	0.031 ± 0.008	0.005	0.983	0.1898	[-9.05 13.20]	0.004	1.1542	[2.64 24.31]	0.039	1.1436	[-0.85 23.66]	OA

Sit-to-Stand

Acoustic Feature	Healthy Mean ± Std. Dev.	Pre-OA Mean ± Std. Dev.	OA Mean ± Std. Dev.	p: Kruskal-Wallis	p: Healthy - pre-OA	Healthy - pre-OA Effect Size	Healthy - pre-OA 95% CI	p: Healthy - OA	Healthy - OA Effect Size	Healthy - OA 95% CI	p: pre-OA - OA	pre-OA - OA Effect Size	pre-OA - OA 95% CI	Model
Spectral spread	1116.876 ± 121.713	991.377 ± 109.381	962.416 ± 146.501	0.005	0.011	1.0321	[1.24 21.11]	0.006	1.1462	[2.03 21.89]	1.000	0.2133	[-10.46 12.01]	Pre-OA
Spectral centroid	1263.179 ± 209.131	1069.432 ± 177.625	991.576 ± 169.689	0.005	0.067	0.9419	[-1.59 18.26]	0.004	1.336	[2.51 22.37]	0.572	0.4268	[-7.13 15.34]	OA
Spectral decrease	0.035 ± 0.004	0.039 ± 0.004	0.040 ± 0.004	0.009	0.051	-0.9749	[-18.73 1.13]	0.014	-1.2268	[-20.73 -0.86]	1.000	-0.282	[-13.23 9.24]	OA
Zero-crossing rate	0.066 ± 0.011	0.055 ± 0.008	0.049 ± 0.008	0.002	0.083	0.9773	[-1.97 17.88]	0.001	1.5536	[4.18 24.05]	0.283	0.6998	[-5.07 17.40]	Both
MFCC 5	1.186 ± 0.050	1.176 ± 0.050	1.201 ± 0.045	0.642	0.918	0.2013	[-7.82 12.03]	0.859	-0.2989	[-12.27 7.59]	0.516	-0.5035	[-15.68 6.79]	OA
MFCC 8	-0.697 ± 0.054	-0.676 ± 0.038	-0.645 ± 0.039	0.051	0.527	-0.4072	[-13.80 6.06]	0.017	-1.0178	[-20.46 -0.60]	0.233	-0.777	[-17.90 4.57]	Pre-OA
Band Power 380-400 Hz	0.162 ± 0.017	0.161 ± 0.012	0.165 ± 0.019	0.885	1.000	0.1179	[-9.64 10.21]	0.961	-0.14	[-11.87 7.99]	0.954	-0.2666	[-13.46 9.01]	Pre-OA

Walking

Acoustic Feature	Healthy Mean ± Std. Dev.	Pre-OA Mean ± Std. Dev.	OA Mean ± Std. Dev.	p: Kruskal-Wallis	p: Healthy - pre-OA	Healthy - pre-OA Effect Size	Healthy - pre-OA 95% CI	p: Healthy - OA	Healthy - OA Effect Size	Healthy - OA 95% CI	p: pre-OA - OA	pre-OA - OA Effect Size	pre-OA - OA 95% CI	Model
Spectral Centroid	309.298 ± 64.290	320.842 ± 40.524	269.003 ± 50.543	0.101	0.720	-0.1939	[-14.03 7.63]	0.140	0.6502	[-3.23 18.43]	0.058	1.0837	[-1.71 23.31]	Pre-OA
Spectral Entropy	0.440 ± 0.039	0.455 ± 0.025	0.417 ± 0.042	0.094	0.497	-0.4196	[-15.23 6.43]	0.200	0.5688	[-4.03 17.63]	0.048	1.0625	[-1.31 23.71]	Pre-OA
Spectral Roll-Off Point	746.215 ± 109.418	761.874 ± 82.621	655.273 ± 139.117	0.104	1.000	-0.1497	[-12.58 9.08]	0.098	0.7416	[-2.48 19.18]	0.080	0.8923	[-2.41 22.61]	Both
Spectral Skewness	1.884 ± 0.750	1.681 ± 0.445	2.494 ± 0.929	0.081	0.794	0.2949	[-7.98 13.68]	0.103	-0.7343	[-19.08 2.58]	0.051	-1.0699	[-23.61 1.41]	OA
Spectral Slope	0.000 ± 0.000	0.000 ± 0.000	0.000 ± 0.000	0.194	0.222	-0.5289	[-17.38 4.28]	0.318	-0.506	[-16.48 5.18]	1.000	-0.0251	[-11.61 13.41]	Pre-OA
Spectral Crest	74.394 ± 15.423	67.441 ± 8.702	80.421 ± 14.906	0.136	0.289	0.4945	[-4.93 16.73]	0.513	-0.3845	[-15.13 6.53]	0.077	-1.0185	[-22.71 2.31]	Both
RMS	0.184 ± 0.076	0.146 ± 0.033	0.151 ± 0.057	0.176	0.183	0.5619	[-3.83 17.83]	0.404	0.4533	[-5.83 15.83]	1.000	-0.1049	[-14.51 10.51]	OA
Log Energy	3.677 ± 1.062	3.314 ± 0.525	3.396 ± 0.937	0.181	0.146	0.3798	[-3.33 18.33]	0.548	0.2665	[-6.73 14.93]	0.773	-0.1033	[-15.91 9.11]	OA
MFCC 0	-14.642 ± 1.539	-15.122 ± 0.534	-15.324 ± 1.394	0.176	0.204	0.356	[-4.08 17.58]	0.295	0.4441	[-4.98 16.68]	1.000	0.1835	[-13.41 11.61]	OA
MFCC 1	6.592 ± 0.216	6.666 ± 0.122	6.450 ± 0.281	0.173	0.860	-0.3789	[-13.38 8.28]	0.204	0.5792	[-4.08 17.58]	0.113	0.9553	[-3.21 21.81]	OA
MFCC 3	0.206 ± 0.133	0.211 ± 0.115	0.330 ± 0.167	0.080	1.000	-0.0435	[-11.08 10.58]	0.052	-0.8393	[-20.38 1.28]	0.113	-0.7932	[-21.81 3.21]	Pre-OA
MFCC 4	-0.926 ± 0.142	-0.936 ± 0.115	-0.777 ± 0.188	0.047	1.000	0.0761	[-9.78 11.88]	0.040	-0.9193	[-20.88 0.78]	0.051	-0.9791	[-23.61 1.41]	OA
MFCC 9	0.015 ± 0.038	0.016 ± 0.021	0.041 ± 0.047	0.116	1.000	-0.0521	[-12.28 9.38]	0.065	-0.6241	[-19.98 1.68]	0.211	-0.6474	[-20.21 4.81]	Pre-OA
MFCC 11	-0.306 ± 0.030	-0.305 ± 0.024	-0.274 ± 0.035	0.060	1.000	-0.0411	[-11.63 10.03]	0.032	-0.9722	[-21.23 0.43]	0.099	-0.9803	[-22.11 2.91]	OA
Band Power 160-175 Hz	0.202 ± 0.053	0.191 ± 0.038	0.233 ± 0.040	0.118	0.906	0.2215	[-8.48 13.18]	0.130	-0.6034	[-18.58 3.08]	0.080	-1.0288	[-22.61 2.41]	Pre-OA
Band Power 175-200 Hz	0.111 ± 0.031	0.115 ± 0.025	0.144 ± 0.035	0.013	0.883	-0.1461	[-13.28 8.38]	0.005	-1.021	[-24.18 -2.51]	0.056	-0.9209	[-23.41 1.61]	OA
Band Power 620-680 Hz	0.045 ± 0.021	0.049 ± 0.013	0.030 ± 0.015	0.079	0.699	-0.2053	[-14.13 7.53]	0.110	0.7418	[-2.73 18.93]	0.044	1.2427	[-1.11 23.91]	Pre-OA
Band Power 850-920 Hz	0.029 ± 0.015	0.030 ± 0.013	0.018 ± 0.009	0.055	0.971	-0.0481	[-11.78 9.88]	0.042	0.8235	[-0.88 20.78]	0.056	1.0217	[-1.61 23.41]	Pre-OA

Supplementary Table 5: Healthy Vs OA Classification Model Performance.

Healthy vs. OA Classification Performance

Movement Type	Healthy Mean \pm S.D.	Arthritic Mean \pm S.D.	P value	Effect Size (Hedge's g)	CI 95%	ROC AUC	Accuracy	Sensitivity	Specificity
Flexion-Extension	0.20 \pm 0.22	0.83 \pm 0.15	<0.005	3.01	[0.49 0.77]	0.97	97%	100%	94%
Sit-to-Stand	0.20 \pm 0.29	0.78 \pm 0.22	<0.005	1.98	[0.35 0.79]	0.93	84%	89%	81%
Walking	0.38 \pm 0.20	0.60 \pm 0.18	0.007	1.07	[0.06 0.38]	0.82	83%	80%	85%
Composite	0.24 \pm 0.22	0.82 \pm 0.13	<0.005	3.17	[0.45 0.71]	0.99	94%	100%	90%
Age / BMI	0.42 \pm 0.22	0.57 \pm 0.21	0.06	0.69	[-0.33 0.01]	0.72	59%	67%	55%

Supplementary Table 6: Healthy vs. All OA (pre-OA and OA) Classification Performance.

Healthy vs. All OA Classification Performance

Movement Type	Healthy Mean \pm S.D.	Arthritic Mean \pm S.D.	P value	Effect Size (Hedge's g)	CI 95%	ROC AUC	Accuracy	Sensitivity	Specificity
Flexion-Extension	0.34 \pm 0.23	0.72 \pm 0.19	<0.005	1.81	[0.24 0.53]	0.88	80%	83%	78%
Sit-to-Stand	0.35 \pm 0.16	0.63 \pm 0.15	<0.005	1.81	[0.16 0.39]	0.91	80%	78%	81%
Walking	0.46 \pm 0.15	0.55 \pm 0.13	0.07	0.64	[-0.01 0.17]	0.70	75%	80%	70%
Composite	0.40 \pm 0.17	0.68 \pm 0.15	<0.005	1.75	[0.17 0.38]	0.89	84%	96%	70%
Age / BMI	0.41 \pm 0.23	0.59 \pm 0.21	0.008	0.82	[0.05 0.33]	0.72	72%	71%	71%

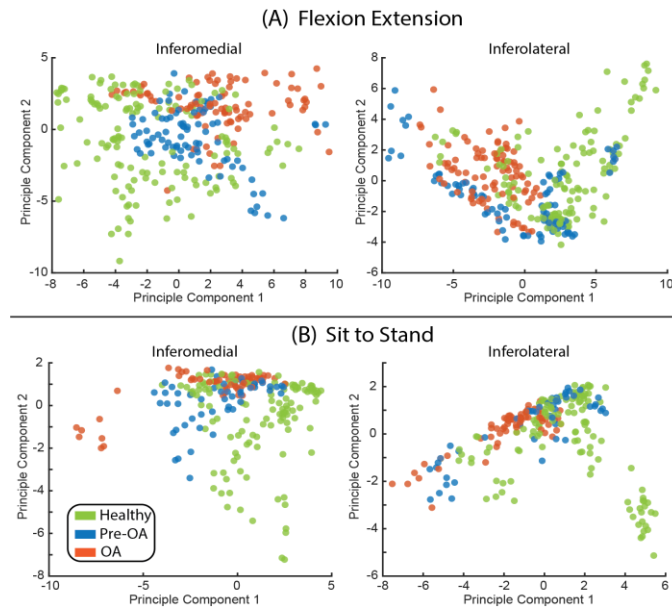
Supplementary Table 7: Multiclass Classification Performance.

Healthy, Pre-OA, and OA Multiclass Classification Performance

Movement Type	Accuracy	Balanced Accuracy	Sensitivity	Specificity	Healthy Accuracy	Pre-OA Accuracy	OA Accuracy
Flexion-Extension	68%	67%	67%	84%	72%	55%	75%
Sit-to-Stand	62%	58%	58%	81%	75%	44%	56%
Walking	60%	60%	60%	79%	60%	60%	60%
Composite	71%	72%	71%	86%	75%	55%	83%
Composite with Pain & Crepitus	70%	69%	68%	85%	75%	55%	75%
Age / BMI	56%	56%	56%	78%	55%	72%	41%

Supplementary Table 8: Averaged-rater intra-class correlation coefficients averaged across microphones for all acoustic features investigated in this study. 10 knees from five participants of varying arthritic severity were recruited, and KAE's were measured four times across two measurement days from each participant. Average-rater ICC values from both inter-session and intra-session comparisons were very high for all scripted maneuvers (0.971 +/- 0.08).

Acoustic Feature	Flexion/Extension Inter-Session	Flexion/Extension Intra-Session	Sit to Stand Inter-Session	Sit to Stand Intra- Session	Walking Inter-Session	Walking Intra- Session
Spectral Spread	0.995	1.000	0.994	1.000	0.981	1.000
Spectral Centroid	0.995	1.000	0.993	1.000	0.987	0.999
Spectral Decrease	0.995	1.000	0.866	1.000	0.908	0.997
Spectral Entropy	0.995	1.000	0.991	1.000	0.981	0.995
Spectral Roll-Off Point	0.995	1.000	0.994	1.000	0.984	1.000
Spectral Skewness	0.993	0.998	0.989	0.999	0.956	0.989
Spectral Slope	0.964	1.000	0.895	1.000	0.899	1.000
Spectral Crest	0.994	0.999	0.986	0.999	0.974	0.999
Zero-Crossing Rate	0.995	0.999	0.994	0.999	0.986	1.000
RMS	0.960	0.969	0.893	0.890	0.879	0.913
Log Energy	0.967	0.995	0.911	0.979	0.866	0.994
MFCC 0	0.975	0.997	0.923	0.993	0.891	0.999
MFCC 1	0.995	1.000	0.992	1.000	0.942	1.000
MFCC 2	0.993	1.000	0.986	1.000	0.859	1.000
MFCC 3	0.989	1.000	0.987	1.000	0.979	0.990
MFCC 4	0.992	1.000	0.986	1.000	0.983	1.000
MFCC 5	0.990	1.000	0.987	1.000	0.983	1.000
MFCC 6	0.988	1.000	0.987	1.000	0.960	0.995
MFCC 8	0.986	1.000	0.981	1.000	0.924	0.994
MFCC 9	0.980	0.987	0.968	0.978	0.946	0.998
MFCC 11	0.959	0.999	0.927	0.999	0.964	1.000
Band Power 380-400 Hz	0.974	0.999	0.945	0.997	0.966	0.998
Band Power 825-870 Hz	0.989	0.999	0.982	0.999	0.984	0.999
Band Power 910-950 Hz	0.991	0.999	0.977	0.999	0.983	0.999



Supplementary Figure 1: Principal component analysis (PCA) of acoustic features from individual microphones for flexion-extension and sit-to-stand maneuvers. PCA was used to reduce the dimensionality of acoustic features to visualize data variability between movement cycles. Inferomedial and inferolateral microphones showed the most separation between clusters, with pre-OA grouping closer to OA than healthy. Pre-OA: early pre-radiographic osteoarthritis; OA: radiographic osteoarthritis.