Wireless multichannel vibroarthrographic recordings for the assessment of knee osteoarthritis during three activities of daily living

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1. Introduction

Osteoarthritis (OA) is the most prevalent joint disease (Vos et al., 2012) and a global issue resulting in chronic pain and impaired mobility. Knee OA represents a scientific challenge accounting for 83% of total OA burden (Vos et al., 2012). Further, the biomechanics of the knee joint are of particular interest due to its weight bearing role, high injury rate and degenerative processes leading to OA (Maffulli et al., 2011). Altered hamstring-quadriceps muscle balance and kinematics have been reported during gait in knee OA (Hortobagyi et al., 2005; O'Connell et al., 2016). These studies confirm the importance of assessing activity of daily living (ADL) in line with the OsteoArthritis Research Society International recommendations for testing physical function in patients with OA (Dobson et al., 2013).

Beside biomechanical assessments of ADL in knee OA, vibroarthrography (VAG) of the knee, i.e., measuring the vibrations reflecting knee crepitus during joint motion has also been used as a non-invasive diagnostic tool as a proposed surrogate model for roughness, softness or lubrication of the cartilage surface (Rangayyan and Wu, 2009; Wu et al., 2010). Since the publication of pioneer work of Blodgett (1902) and Walters (1929), the study of the knee joint VAG signal has gained in sensitivity due to improvements in micro-electronics and specificity due to advanced signal processing (Andersen et al., 2018; Krecisz and Baczkowicz, 2018). Similar to the progress made in surface electromyography (Frigo and Crenna, 2009) or mechanomyography (Madeleine et al., 2007), technological advances have also enabled to record multi-channels VAG of the knee joint (Andersen et al., 2018; Befrui et al., 2018; Wiens et al., 2016). In these studies, two to eight miniature accelerometers have been attached over the skin of the knee of participants enabling to assess spatial dependencies of the VAG signals by calculating VAG topographical maps. Variations in the internal pressure distribution applied to cartilage and synovial fluid explain non linearity and spatial dependencies of the compound VAG signal (Neu et al., 2008; Wu et al., 2016).We have

recently showed non-uniform distribution of VAGs during knee flexion-extension movement (Andersen et al., 2018). More specifically, combining linear and nonlinear parameters has improved our understanding of the VAG signals. As such, the use of multichannel VAG recordings and advanced processing approaches has been suggested to discriminate between knee OA patients and asymptomatic participants and between different types of ADL (Andersen et al., 2018). However, no studies have used multichannel VAG to delineate differences among knee OA patients and asymptomatic participants during ADL.

Studies assessing the changes in VAG in knee OA patients compared with asymptomatic participants have shown high accuracy, sensitivity and specificity (Wu, 2015). Especially, the existing body of VAG literature has revealed increased amplitude, absolute variability and frequency contents in knee OA patients compared with asymptomatic participants (Baczkowicz et al., 2017; Baczkowicz and Majorczyk, 2016; Tanaka and Hoshiyama, 2012). Changes in the regularity of the VAG have also been reported confirming that nonlinear analyses provide genuine VAG information (Wu et al., 2016). As previous clinical studies using multichannel VAG have only investigated source localisation or classification issues during knee flexion-extension (Rangayyan and Wu, 2009; Wu et al., 2010), information concerning the spatial dependencies of linear and nonlinear parameters during ADL is lacking.

The purposes of this study were to collect and analyse wireless multichannel VAG topographical maps and characteristics in knee OA patients and asymptomatic participants during ADL. We hypothesised (i) that higher VAG amplitude, variability and frequency contents as well as changed VAG regularity would characterise knee OA patients compared with asymptomatic participants (Baczkowicz et al., 2017; Wu et al., 2016), (ii) that VAG recordings would differentiate between ADL types (Andersen et al., 2018) and (iii) the presence of non-uniform distribution of VAGs (Andersen et al., 2018). If confirmed, the

present technique could be used in clinical practise to objectively assess motor function during some typical ADL.

2. Methods

2.1. Design

The present investigation was a cross-sectional study involving patients suffering from knee OA and asymptomatic participants. The study was conducted according to the ethical guidelines of the Helsinki Declaration and was approved by the North Denmark Region Committee on Health Research Ethics (VN-20160081). All participants provided written informed consent.

2.2. Participants

Twenty knee OA patients (11 males and 9 females) were recruited from a database at the Centre for Clinical and Basic Research (CCBR, Aalborg, Denmark) and 20 asymptomatic participants (10 males and 10 females) were recruited from the dwelling community (Table 1). Knee OA patients were diagnosed in accordance with American College of Rheumatology classification (Kellgren and LAWRENCE, 1957). Participants were screened for inclusion by a medical doctor at CCBR. Inclusion criteria for knee OA patients included age 18-80, clinically diagnosed knee OA with Kellgren-Lawrence grade ≥ 2, self-reported pain during walking and BMI <35, no use of painkillers in the 24 hours prior to experimentation. Inclusion criteria for asymptomatic participants were age 18-80, no diagnosed knee OA, no self-reported pain during walking and BMI <35, no use of painkillers in the 24 hours prior to experimentation. Exclusion criteria were pregnancy, drug addiction, lack of ability to cooperate and, participation in other pain trials throughout the study period.

2.3. Experimental protocol

All participants participated in one session and they all completed the entire session. The same experimenter (R.E.A.) conducted all tests. The participants performed three different types of ADL in a counterbalanced order: (i) 5 repetitions of sit to stand movement (ii) Stairs descent (10 stairs). (iii) Stairs ascent (10 stairs) in line with the recommendations for testing physical function in patients with OA (Dobson et al., 2013). The sit to stand exercise were carried out at a slow pace (60-s were allowed for the five repetitions). Arms were maintained along the body side through the sit to stand exercise (Malling and Jensen, 2016). Hands were not used during raising movement from the chair. Stairs descent and ascent were carried out without using the hand railing at the slowest speed that the participants were comfortable with while maintaining balance. Pain intensity was assessed using a visual analogue scale ("0": no pain and "10": worst pain imaginable) after sit to stand and stairs descent-ascent.

2.4. Vibroarthrographic recording

VAG recording was carried out using a custom-made device based on a Trentadue wireless multichannel recorder (OT Bioeletronica, Torino, Italy), a custom 16 channel accelerometers adaptor and micro machined accelerometers LIS344ALH (ST microelectronics, Geneva, Switzerland). The setup has a sensitivity of 600 mV/g and 0-1800 Hz linear transmission. The recording probe is composed of an accelerometer chip supporting board set up to only record acceleration in the orthogonal direction. The probe weight is approx. 0.75 g with wire and has an 8.5×7 mm size. The VAG device contains a 10-500 Hz band-pass filter. Gain was set to 3 and the VAGs were sampled at 2000 Hz. The VAGs were recorded using a custom script (IOIVibcorder, Aalborg University, Aalborg, Denmark) implemented in Matlab 2016a (The MathWorks, Inc, Natick, Massachusetts, United States).

During ADL tests, the recording device was placed in a belt bag around the waist of the participant with wires attached to the thigh allowing natural movement. Eight accelerometers were placed on the most painful knee of the knee OA patients (right knee for all patients but

one due to knee surgery). The accelerometers were placed accordingly (right knee for all but one) for the asymptomatic participants. Accelerometers were attached to the skin with double side tape. Four accelerometers separated by 1-2 cm were placed on the participant's patella in a square configuration. One accelerometer was placed on the tibial tuberosity below the patella, two were placed respectively on the lateral side of the knee 1-2 cm from the lateral epicondyle and on the medial side of the knee 1-2 cm from the medial epicondyle of femur towards the patella. The last accelerometer was placed above the knee over the quadriceps tendon in line with our previous study (Andersen et al., 2018), see Fig. 1. Special attention was given to ensure that motion did not loosen the accelerometers attachment.

2.5. Data analysis

Data preprocessing and VAG parameter extraction were carried out using Matlab. Preprocessing consisted of conversion of VAG signals into SI units (ms^{-1}) and digital filtering using a bandpass FIR filter using a Kaiser windowed, 10-500 Hz (1453-points, beta: 5.6533). Epochs containing the beginning and end of the recorded ADL were extracted and the outcome parameters were processed across time. A recent literature review conducted by the authors [1] has shown that six parameters are likely to thoroughly depict the characteristics of the VAG signal. Thus, we computed the following parameters (Table 2) over the extracted epochs: (i) averaged rectified values (ARV); (ii) mean power frequency (MPF), (iii) variance of means squared (VoMS), (iv) form factor (FF), (v-vi) the % of determinism and recurrence (%DET and %REC). Recurrence quantification analysis (RQA) was applied using the z-scored data (Nalband et al., 2016). The %REC parameter is the percentage of recurring points in the recurrence matrix below the tolerance threshold (see below). The %DET parameter is the percentage of recurrence points forming diagonal lines in the recurrence plot of at least length 2. %REC and % DET increases as the signal becomes more regular (Liu et al., 2004). The embedding dimension, delay and tolerance values were as defined in (Andersen et al.,

178 2018) to allow for easier comparison. Using the nearest neighbour approach (Kennel et al.,
179 1992) the embedding dimension was set to 5. Using an approach based on the drop of auto
180 correlation function below 0.2, the delay parameter was set to 19 ms. Using a %REC
181 minimization optimization method tolerance was set to 0.2839.

182 *2.6. Statistical analysis*

183 Statistical analysis carried out using SPSS version 23 (IBM Corp., Armonk, NY, USA). A
184 linear mixed model with *group* (knee OA patients and asymptomatic participants), *ADL* (sit
185 to stand, stairs descent and stairs ascent) and *location* (1-8) as within subject factors for each
186 of the parameters. All interactions between factors were included in the model. To allow for
187 residuals with unequal variance, a repeated factor associated with patient type, ADL type and
188 location was added to the model. When a significant effect was observed, a Bonferroni
189 adjustment was performed for a pairwise comparison. Data are presented in the results
190 section as mean (SE). P values < 0.05 were considered significant.

191

192 **3. Results**

193 *3.1. Participant characteristics*

194 The demographic data showed that the asymptomatic participants were older than the knee
195 OA patients but similar in terms of gender distribution, body height and body mass (Table 1).
196 Table 3 shows the overall results of the statistical analysis.

197 *3.2. Differences between knee osteoarthritis patients and asymptomatic participants*

198 *Group* played a significant role for ARV and %REC. Higher ARV (0.535 (0.033) $mm*s^{-2}$ vs.
199 0.399 (0.033) $mm*s^{-2}$, P = 0.006) and lower %REC (0.120 (0.048) % vs. 0.345 (0.049) %, P
200 = 0.001) were found for knee OA patients compared with asymptomatic participants (Fig. 2i
201 and 2v).

202 *3.3. Differences among activities of daily living*

ADL played a significant role for all parameters except %REC (Fig. 2i-iv and 2vi). ARV were lowest during sit to stand (0.187 (0.027) $mm*s^{-2}$), intermediate during stairs ascent (0.502 (0.024) $mm*s^{-2}$) and highest during stairs descent (0.703 (0.026) $mm*s^{-2}$, $P < 0.001$). VoMS were smaller during sit to stand (0.270 (0.035) mm^4*s^{-8}) than both stairs ascent (0.907 (0.052) mm^4*s^{-8}) and stairs descent (1.070 (0.050) mm^4*s^{-8}, $P < 0.001$). MPF were higher during sit to stand (123.7 (3.7) Hz) than both stairs ascent (65.4 (3.1) Hz) and stairs descent (61.8 (3.2) Hz, $P < 0.001$). VoMS was also lower during stairs ascent than during stairs descent ($P < 0.032$). FF were lowest during sit to stand (2.114 (0.066) a.u.) than both stairs ascent (3.367 (0.081) a.u.) and stairs descent (3.500 (0.084) a.u., $P < 0.001$). %DET were lowest during sit to stand (24.750 (2.271) %), intermediate during stairs ascent (42.787 (2.053) %) and highest during stairs descent (48.804 (2.026) %, $P < 0.001$).

3.4. Differences among location

Location played a significant role for all parameters; see Table 4 for the result of the pair wise comparisons (Fig. 2i-vi). Lower ARV were recorded on the patella and the tibial tuberosity ($P < 0.05$). VoMS and FF were lower on the patella and higher on the medial condyle ($P < 0.05$). Higher MPF were found on the patella and on the tibial tuberosity ($P < 0.05$). Higher %REC were recorded on the patella and the medial condyle ($P < 0.05$). Finally, lower %DET were found on the patella ($P < 0.05$).

3.5. Interactions between group, ADL and location

There were significant *Group* × *ADL* interactions for %DET. The %DET was lowest during sit to stand than during stairs ascent and stairs descent as well as lower during stairs ascent than stairs descent for and asymptomatic participants ($P < 0.001$). The %DET was lower during sit to stand than during stairs descent and lower during stairs ascent than stairs descent for knee OA patients ($P < 0.001$). There were also significant *ADL* × *Location* interactions for ARV, VoMS, FF and %REC. The pair wise comparisons showed that ARV were lower

during sit to stand than both stairs ascent and descent and lower during stairs ascent than stairs descent for *location* 1-8 ($P < 0.001$). The pairwise comparisons showed that VoMS and FF were lower during sit to stand than both stairs ascent and descent for *location* 1-8 ($P < 0.014$ and $P < 0.001$, respectively). The pair wise comparisons showed that %REC were lower during sit to stand than both stairs ascent and descent for *location* 2 ($P < 0.001$) and during sit to stand than stairs descent for *location* 3 ($P < 0.05$).

4. Discussion

Spatial dependencies depicted by multichannel VAG recordings from knee OA patients and asymptomatic participants were investigated for the first time during ADL. Partly in line with our first hypothesis, higher VAG amplitude and lower VAG regularity characterised knee OA patients compared with asymptomatic participants. The present study also confirmed as hypothesised that wireless multichannel VAG recordings can differentiate between ADL types and depict non-uniform spatial distribution of knee joint VAG.

4.1. Differences in vibroarthrography between knee osteoarthritis patients and asymptomatic participants

The recordings of VAG provide clinically relevant information related to biomechanical and friction features reflecting the condition of the joint (Shieh et al., 2016; Stoltze et al., 2017). In this study, we computed a series of parameters representing signal amplitude, frequency contents, absolute and relative variability as well as VAG regularity. The ARV of the VAGs were higher in knee OA patients compared with asymptomatic participants in line with previous studies (Baczkowicz et al., 2017; Baczkowicz et al., 2019; Baczkowicz and Majorczyk, 2016; Tanaka and Hoshiyama, 2012). Contrary to these studies and to our hypothesis, the MPF, VoMS and FF of the VAGs did not differ in this population of knee OA patients compared with asymptomatic participants. Differences in the studied populations and

253 the VAG processing mostly explain these differences. The %REC of the VAGs were lower in
254 knee OA patients compared with asymptomatic participants underlining that the VAGs were
255 less regular (Liu et al., 2004). Such increases in amplitude and decreases in regularity mostly
256 underlined differences in the internal pressure distribution on the cartilage and in synovial
257 fluid in knee OA (Neu et al., 2008) as well as altered muscle activation (Hortobagyi et al.,
258 2005). This is also corroborated by previous VAG studies reporting articular surface with
259 chondral lesions and higher friction in knee OA (Baczkowicz et al., 2019; Baczkowicz and
260 Majorczyk, 2016; Stoltze et al., 2017; Wu et al., 2016). Increased roughness of cartilage has
261 been shown to alter arthrokinematic motion (Lorenz et al., 2013). The parameters assessing
262 the amplitude and regularity of the VAG signals characterize the biomechanical aspects of
263 movement pattern, e.g., joint loading. The current study also suggest that these parameters are
264 likely to be associated with joint degenerations in OA patients, confirming the importance of
265 using linear and nonlinear analytic methods in VAG studies (Andersen et al., 2018).
266 *4.2. Activities of daily living and vibroarthrography*
267 We chose to study sit to stand, stairs descent and ascent, which are considered normal ADL,
268 as well as functions recommended to examine patients with knee OA (Dobson et al., 2013).
269 Many VAG studies have studied open kinetic chain movements most likely to avoid artefacts
270 during to e.g., heel strike (Andersen et al., 2018). On the other hand, these movements do not
271 reflect the biomechanical load applied to the patellofemoral joint occurring during closed
272 kinetic chain movements characterising ADL (Baczkowicz et al., 2019). A cadaveric model
273 study has shown that the contact stress applied to the patellofemoral joint can be up to 16
274 times higher during squat compared with open chain kinetic movement (Cohen et al., 2001).
275 A few studies have investigated sit to stand (Baczkowicz et al., 2019; Shark et al., 2011;
276 Tanaka and Hoshiyama, 2012; Wiens et al., 2016). Bączkowicz et al. (2019) have suggested
277 that the high contact stress would occur along increased kinetic friction and result in higher

amplitude, variability and frequency contents of the VAG signal. A biomechanical study has reported correlations between the amplitude of the VAG signal and the estimated relative total knee compressive force (Stoltze et al., 2017). To the best of our knowledge, no studies have investigated VAG during stairs descent or ascent. Stairs descent is usually studied in relation to patellofemoral pain due to increased compressive force applied to the joint (Rathleff et al., 2013). All the computed parameters beside %REC differentiate between the three types of ADL. The ARV, VoMS, FF and %DET were lowest during sit to stand compared with stairs ascent and descent. Further, ARV and %DET were higher during stairs descent compared with stairs ascent mostly due to increased compressive forces during ADL. The results related to amplitude and variability of the VAG signal during closed chain kinetic movement were in line with Bączkowicz et al. (2019) but differed for frequency contents. Here too, differences in signal processing (epoch length, frequency computation) and movement artefacts mostly explain this discrepancy. Overall, the current findings confirmed that wireless VAG recordings can be used to study ADL offering important perspectives for future clinical studies targeting knee OA in ecological environment.

4.3. Spatial dependencies in vibroarthrography

A novel aspect of the current study relates to its ability in revealing non-uniformity of the VAG spatial distribution during the three studied ADL as well as differences in VAG spatial distribution among knee OA patients and asymptomatic participants. The accelerometer location influenced the computed parameters, all showing different patterns of uneven acceleration dampening in agreement with Andersen et al. (2018). When comparing locations, lower VAG amplitudes were found on the patella and the tibial tuberosity. In parallel, lower and higher absolute and relative variability were seen on the patella and the medial condyle, respectively. Finally, higher frequency contents were found on the patella and on the tibial tuberosity while more (%REC) and less (%DET) regular VAG signals were

303 recorded on the patella underlining that underlying knee structures affect the VAG signals.
304 Differences in the VAG maps between lateral and medial side of the knee are likely to be
305 related to the distribution of internal forces during ADL (Stoltze et al., 2017). Confirming
306 recent findings, the computed parameters revealed unique features of the VAG signals
307 underlining the importance of reporting these distinct parameters. Multi-channel VAG
308 recordings open new possibilities enabling to identify the unique signature of a pathological
309 knee as well as to assess the effect of interventions based on, e.g., strength training or knee
310 braces.

311 *4.4. Limitations*

312 A main limitation of the present study is its cross-sectional design which confined us to study
313 group of 20 participants' differences. This type of design does not allow inferring whether the
314 reported changes in VAGs are a source or a cause of knee OA. However, changes in VAGs
315 appear with ageing, supporting the influence of degenerative processes (Baczkowicz et al.,
316 2015). The studied ADL were conducted at self-chosen paces during sit to stand and stairs
317 descent or ascent (Malling and Jensen, 2016; Rathleff et al., 2013). The VAGs were processed
318 across time due to the lack of temporal information beside the onset and offset of movement.
319 Future VAG studies applying segmentation to movement phases and studying the effects of
320 movement artefacts on VAGs are therefore warranted.

321

322 **5. Conclusions**

323 This study revealed spatial dependencies of VAG topographical features in knee OA patients
324 and asymptomatic participants during ADL. Multichannel VAG recordings enabled to
325 differentiate between knee OA patients and asymptomatic participants in terms of VAG
326 amplitude and regularity. The present study also demonstrated the feasibility of wireless

multichannel VAG recordings for assessing different ADL types offering new perspectives for ecological biomechanical assessments of the knee joint.

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Declaration of competing interest

All authors declare no conflict of interest.

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471 **Table 1**. Baseline demographic and clinical characteristics of participants

Variables	Knee Osteoarthritis Patients (n=20)	Asymptomatic Participants (n=20)
Age (years)	66.2 (5.2)	70.3 (5.9)*
Sex (female/male)	9/11	10/10
Body height (cm)	169.8 (9.0)	169.0 (10.8)
Body mass (kg)	77.7 (9.9)	81.5 (13.0)
Body mass index (kg/cm^2)	28.1 (2.7)	27.2 (3.2)
Kellgren Lawrence score (left/right)	2.6 (0.9)/2.6 (0.5)	NA/NA
Pain intensity after sit to stand (VAS)	4.8 (2.7)	0 (0)‡
Pain intensity after stairs descent and ascent (VAS)	5.5 (2.3)	0 (0)‡

472 Values are presented as mean (SD). NA: Not available. VAS: Visual analogue scale

473 * P<0.05. ‡ P<0.001

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475 **Table 2**. List of the extracted vibroarthrographic variables

Variables	**Interpretation**
Averaged rectified values (ARV)	Signal amplitude
Mean power frequency (MPF)	Frequency contents of the signal
Variance of means squared (VoMS)	Absolute reliability
Form factor (FF)	Relative reliability
% of determinism and recurrence (%DET and %REC)	Changes in periodicity of the time series

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Table 3. Results of the statistical analysis on averaged rectified value (ARV), variance of means squared (VoMS), form factor (FF), mean power frequency (MPF), % of Recurrence (%REC) and % of Determinism (%DET) of the vibroarthrographic signals with group (knee osteoarthritis patients-asymptomatic participants), activity of daily living (sit to-stand, stairs descent and ascent) and accelerometer location (1-8) as within factors of the linear mixed model.

	ARV	VoMS	FF	MPF	%REC	%DET
Group	$F_{1,40.828}$=8.502, P=0.006	$F_{1,105.292}$=1.065, P=0.304	$F_{1,50.502}$=0.309, P=0.581	$F_{1,39.970}$=0.862, P=0.359	$F_{1,181.925}$=10.632, P=0.001	$F_{1,38.732}$=0.075, P=0.786
ADL	$F_{2,260.230}$=313.495, P<0.001	$F_{2,460.450}$=160.790, P<0.001	$F_{2,453.152}$=272.893, P<0.001	$F_{2,412.177}$=232.835, P<0.001	$F_{2,126.192}$=0.200, P=0.819	$F_{2,365.519}$=135.774, P<0.001
Location	$F_{7,127.592}$=17.175, P<0.001	$F_{7,141.649}$=11.975, P<0.001	$F_{7,147.421}$=45.795, P<0.001	$F_{7,178.344}$=38.945, P<0.001	$F_{7,156.097}$=2.920, P=0.007	$F_{7,145.089}$=11.571, P<0.001
Group × *ADL*	$F_{2,260.230}$=1.012, P=0.365	$F_{2,460.450}$=2.080, P=0.126	$F_{2,453.152}$=0.250, P=0.779	$F_{2,\ 412.177}$=2.697, P=0.069	$F_{2,126.192}$=0.030, P=0.970	$F_{2,365.519}$=5.085, P=0.007
Group × *Location*	$F_{7,127.592}$=1.531, P=0.162	$F_{7,141.649}$=0.500, P=0.833	$F_{7,147.421}$=1.692, P=0.115	$F_{7,178.344}$=1.914, P=0.070	$F_{7,156.097}$=2.514, P=0.018	$F_{7,145.089}$=0.781, P=0.604
ADL × *Location*	$F_{14,96.408}$=2.754, P=0.002	$F_{14,139.014}$=2.201, P=0.010	$F_{14,148.128}$=3.528, P<0.001	$F_{14,107.429}$=1.405, P=0.163	$F_{14,111.443}$=2.591, P=0.003	$F_{14,108.071}$=0.445, P=0.956
Group × *ADL* × *Location*	$F_{14,96.408}$=0.221, P=0.999	$F_{14,139.014}$=0.420, P=0.966	$F_{14,\ 148.128}$=0.742, P=0.729	$F_{14,107.429}$=0.557, P=0.892	$F_{14,111.443}$=0.567, P=0.886	$F_{14,108.071}$=0.219, P=0.999

Table 4. Results of the pairwise comparison for average rectified values (ARV), variance of means squared (VoMS), form factor (FF), mean power frequency (MPF), and % of Determinism (%DET) for locations ($P \leq 0.05$). In each cell, the mentioned parameters corresponding to the location indicated along the rows was compared with the remaining locations.

	Location 1	Location 2	Location 3	Location 4	Location 5	Location 6	Location 7	Location 8
Location 1	-	ARV< VoMS< FF< MPF> %DET<	ARV< VoMS< FF< MPF> %DET<	ARV< VoMS< FF< MPF> %DET<	ARV< FF< MPF>	ARV< VoMS< FF< MPF> %DET<	ARV< VoMS< FF< MPF> %DET<	ARV< VoMS< FF< MPF>
Location 2	-	-	VoMS< FF< MPF>	MPF>	ARV> FF>	VoMS< FF< MPF>	NS	ARV> FF>
Location 3	-	-	-	NS	ARV> VoMS> FF> MPF< %DET>	NS	NS	VoMS> FF> MPF< %DET>
Location 4	-	-	-	-	ARV> VoMS> FF> MPF<	NS	NS	ARV> FF> MPF<
Location 5	-	-	-	-	-	ARV< VoMS< FF< MPF> %DET<	ARV< VoMS< FF< MPF> %DET<	NS
Location 6	-	-	-	-	-	-	MPF<	ARV> VoMS> FF> MPF< %DET>
Location 7	-	-	-	-	-	-	-	ARV> FF> MPF< %DET>
Location 8	-	-	-	-	-	-	-	-

NS: Non significant.

Figure legends:

Fig. 1: Accelerometer locations. Accelerometers were placed over the quadriceps tendon (1), the lateral side of the knee approx. 1-2 cm medial from the epicondyle of femur towards the patella (2), lateral proximal on the patella (3), medial proximal on the patella (4), lateral distal on the patella (5), medial distal on patella (6), the medial side of the knee approx. 1-2 cm medial from the epicondyle of femur towards the patella (7), and the tibial tuberosity (8). Example of the micro machined accelerometer mounted on a printed circuit board used to record the vibroarthrographic signals.

Fig. 2: Average maps of the (i) averaged rectified values (ARV, $mm*s^{-2}$), (ii) mean power frequency (MPF, Hz), (iii) variance of means squared (VoMS, $mm^{-4}*s^{-8}$), (iv) form factor (FF, a.u.), (v) % of recurrence (%REC), and (vi) % of determinism (%DET) of the vibroathrographic signals recorded using eight accelerometers (black dots) during activities of daily living (sit to stand, stairs descent and stairs ascent) among patients with knee osteoarthritis (n=20) and asymptomatic participants (n=20). See Fig. 1 for accelerometer nomenclature.

Figure 1

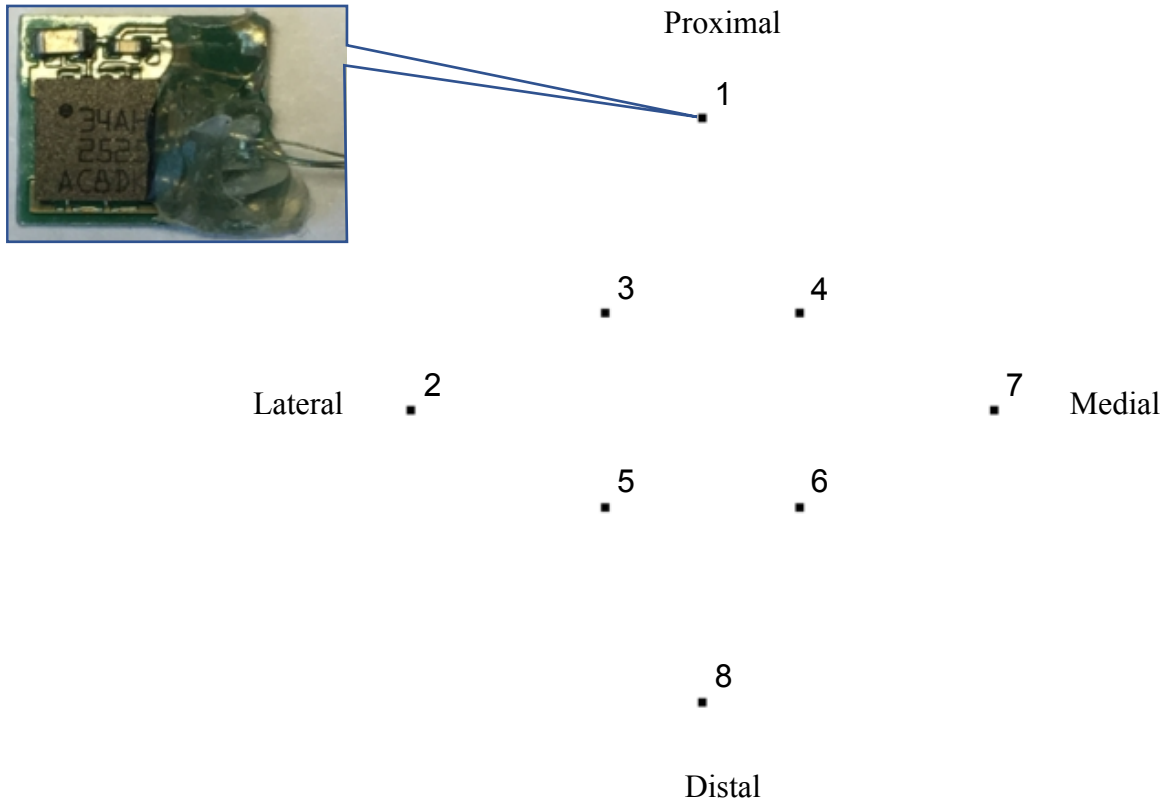
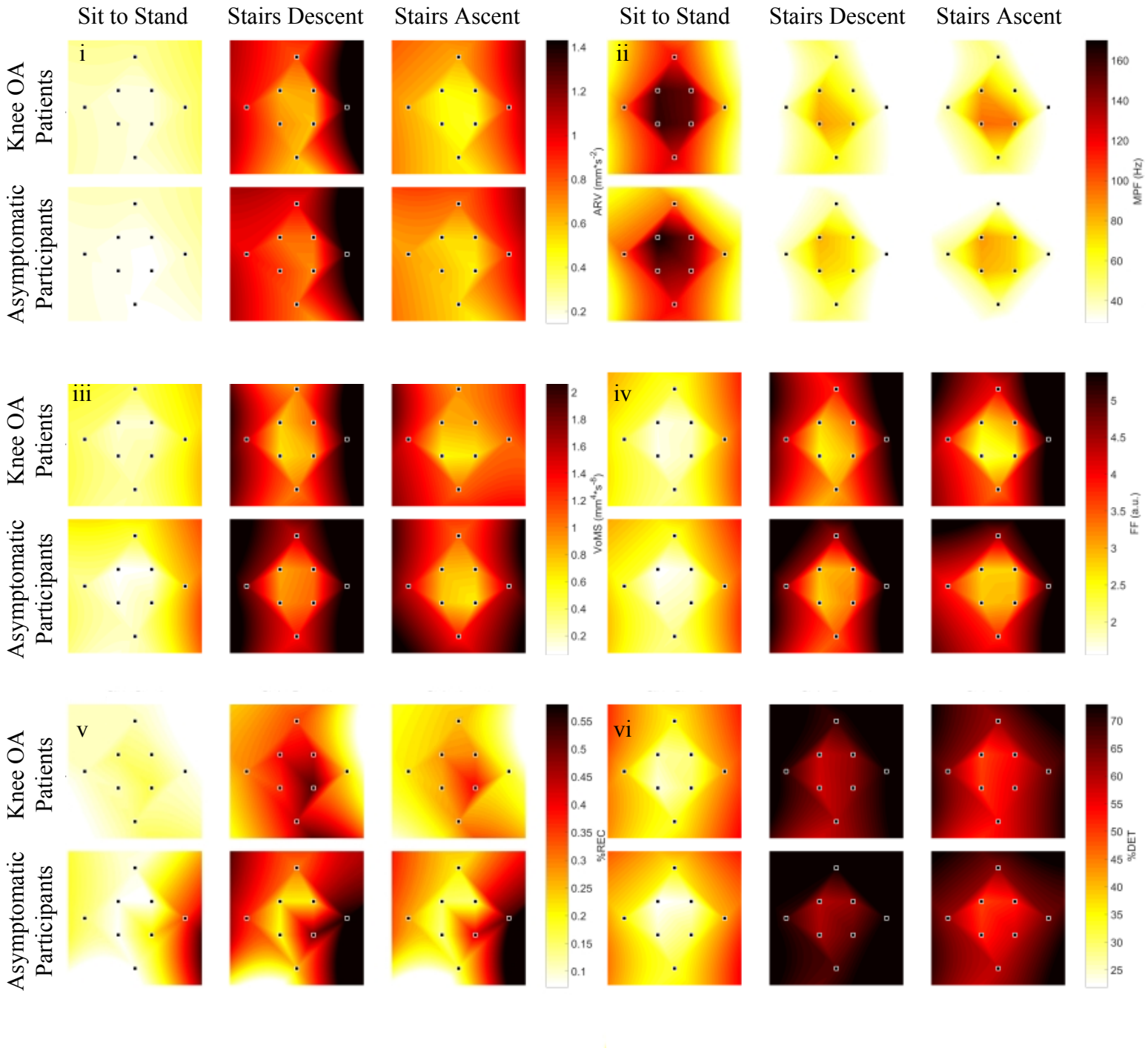


Figure 2


Sit to Stand
Stairs Descent
Stairs Ascent
Sit to Stand
Stairs Descent
Stairs Ascent
Knee OA Patients
Asymptomatic Participants
i
ii
iii
iv
v
vi
ARV (mm²s⁻²)
MPF (Hz)
VoMS (mm⁴s⁻⁵)
FF (a.u.)
%REC
%DET