2023 45th Annual International Conference of the IEEE Engineering in Medicine & Biology Society (EMBC) | 979-8-3503-2447-1/23/$31.00 ©2023 IEEE | DOI: 10.1109/EMBC40787.2023.10340224

Acoustic emissions and age-related changes of the knee

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***Abstract*— Acoustic emission (AE) monitoring is currently being widely investigated as a diagnostic tool in orthopedics, in particular for osteoarthritis (OA) diagnostics. Considering that age is one of the main risk factors for OA, investigating age-related changes in joint AEs might provide an additional incentive for further studies and consequent translation to clinical practice. The aim of this study is to investigate age-related changes in knee AE and determine AE hit definition modes as well as AE hit parameters that allow for improved age group differentiation. Knee AEs were recorded from 51 participants in two age groups (18-35 and 50-75 years old) whilst cycling with 30 and 60 rpm cadence. Two AE sensors with 15-40 kHz and 100-450 kHz frequency ranges were used, and three AE event detection modes investigated. Additionally, participants' Knee Osteoarthritis Outcome Scores (KOOS) were recorded. Low frequency sensors (15-40kHz) and hit modes with shortened hit and peak definition times showed the potential to distinguish between age groups. Moreover, a weak correlation was found between only three parameters (AE event median duration, rise time, and signal strength) and age, indicating that changes in joint AE are most likely associated with pathological changes rather than physiological ageing within the healthy norm.**

***Clinical Relevance*— the use of AE monitoring was examined in the context of age-related changes in knee health. The study indicates the potential for knee AE monitoring to be used as a quantitative measure of pathological changes in the knee status.**

I. INTRODUCTION

Joint disorders, in particular osteoarthritis (OA), are widespread in the older population, with the global prevalence of knee OA estimated at 16%, and an incidence rate of 203 per 10,000 person-years [1]. Taking into account the current high obesity rates and the ageing population, which are known risk factors of OA [2], the numbers suffering from OA are predicted to increase in the future decades [3]. Chronic pain and disability caused by OA are significant public health problems, complicated by the lack of drugs available to halt or reverse the disease's progression [4].

Multiple methods are currently used for orthopaedic assessment of OA and monitoring of the disease progression; however, those methods are often limited to clinical settings and require high-cost equipment such as MRI or radiography or specifically trained clinical professionals to assess the imaging data (e.g. ultrasound). With the growing interest in remote monitoring and personalized medicine, the methods that are suitable for such applications are actively gaining attention in recent years [5]. In particular, the use of acoustic emission (AE) monitoring is one of the alternatives to traditional imaging that has been adopted from industrial applications for non-destructive testing. One of the common approaches used in industrial AE monitoring is that of AE event detection, where an AE event or hit is determined by an amplitude threshold of the acoustic signal in conjunction with pre-set timing parameters. In particular, the hit definition time (HDT) determines the time between acoustic signal crossings of a defined threshold, allowing for the identification of the start and end of the AE event. Peak definition time (PDT), determines the time when the peak of the AE waveform is detected; and hit lockout time (HLT) describes a period of time when AE events are not detected, thus excluding potential signal reflections [6]. While this approach is widely adopted in industry, only a relatively small number of studies have used it in orthopaedic applications. To the best of the authors' knowledge, the afore mentioned pre-set hit definition parameters as well as parameters describing the AE hits, such as amplitude, duration, signal strength, etc. have not been considered in detail, in particular in the context of age-related changes. Considering that age is one of the main risk factors associated with the development of knee OA, investigating age-related changes in joint AE can shed light on the potential of the method. This study therefore aims to investigate different hit definition parameters and identify AE hit features that allow for better differentiation between age groups.

II. METHODS

The study was conducted according to the guidelines of the Declaration of Helsinki and approved by the Clinical Research Ethics Committee of the Cork Teaching Hospitals at the University College Cork (Ref. number: ECM 4 (e) 17/05/2022 & ECM 3 (kkk) 17/05/2022). A total sample size of 32 participants (16 per age group) was calculated using $\alpha=0.05$ and $\beta=0.20$, and an estimated standard deviation and mean number of AE events for older and younger adults during sit-to-stand motion [7]. Participants were solicited for the study by email and word of mouth. Overall, 26 older adults (OG) aged 50 to 75, and 25 younger people (YG) aged 18 to 35 were recruited. Acute injuries or any conditions that may hinder participants from cycling safely and comfortably were set as exclusion criteria. Table I displays the anthropometric and demographic data for the sample groups.

A. Joint AE recording

The USB AE Node system (Mistras) with a sampling rate of 5 Msps and 20 dB gain was used to record knee AEs. Two

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* This research was funded by Science Foundation Ireland (SFI) under Grant number 12/RC/2289-P2 (INSIGHT) and 16/RC/3918 (CONFIRM) which are co-funded under the European Regional Development.

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TABLE I. ANTHROPOMETRICS AND DEMOGRAPHICS: AGE GROUPS

Group	Age, years	Gender	Height, cm	Weight, kg	BMI, kg/m2
OG	60.85 (8.81)	12 females, 14 males	172.86 (1.20)	79.89 (15.08)	26.68 (4.09)
YG	27.64 (4.49)	12 females, 13 males	171.88 (7.76)	71.73 (14.21)	24.16 (3.88)

sensors with different frequency ranges were used: a low frequency AE sensor PK3I [8] (LF) and a high frequency sensor PK15I [9] (HF) with the operating frequencies of 15-40 kHz and 100-450 kHz respectively. As both sensor and AE node system amplify the signal, for hit detection, a threshold of 28 dB was used for the LF sensor and 24 dB for the HF sensor. Three methods of AE hit definition were considered in this study (Table II).

TABLE II. AE HIT DEFINITION PARAMETERS

Mode	PDT, µs	HDT, µs	HLT, µs	Notes
1	40	80	40	Based on the speed of sound in the cancellous bone and average knee size (see Appendix)
2	50	200	300	Recommended for non-metal composite structures [6]
3	200	800	1000	Previously used in literature for OA and age-related damage evaluation [7], [10]

The recoding method was based on previous works [11], [12] with the sensor fixed in place using a foam holder and double-sided medical tape on the right medial tibial condyle area [13]. Cycling was used to excite the joint AEs, while avoiding the influence of body mass (e.g., sit-to-stand exercises [14]) or individual differences in exercise execution (e.g. knee flexion [11], [15]). Approximately one minute of cycling was carried out for each mode and pace (30 and 60 rpm) was recorded, and then repeated with the second sensor, yielding a total of twelve records for each participant (3 modes x 2 cadences x 2 sensors). The record type denoted below as *Sensor_Mode_Cadence*, where *Sensor* - HF or LF; *Mode*-1, 2 or 3; *Cadence* – 30, 60, e.g. LF_1_30.

A metronome and speed display were utilized to help participants maintain a stable cadence throughout the exercise. The lowest cycling resistance was used to ensure all participants were able to cycle for 12 minutes in total, irrespective of fitness level. Xsens (Xsens Technologies B.V., Enschede, Netherlands) inertial measurement units (IMUs) were attached to the stationary bike's crank as well as to the participant's shank and thigh. An extra bespoke IMU [16] was placed on the shank along with Xsens in order to collect timestamps and synchronise the recordings. The experimental setup is presented in Figure 1.


Figure 1. Experimental setup

The AEwin software (Mistras, Physical Acoustic) was used to record and export knee AEs. The IMU recordings were synchronised with the AE data using timestamps and analysed in MATLAB (Mathworks). The first rotation of the cycling exercise was excluded from all the records to avoid potential acoustic artefacts from placing the foot on the pedal. Rotations were also excluded if they differed from the assigned cadence by more than 20%. Overall, 40 rotations at 60 rpm and 20 rotations at 30 rpm were consecutively included, resulting in records of approximately 40s. The recordings were filtered to contain AE hits with a duration greater than 1µs. Additionally, records were filtered to include only high amplitude hits. Such filtering approaches based on hit duration and/or amplitude are often employed in non-destructive AE testing [17]. The thresholds were chosen based on the values previously used in the literature, with 32dB for HF sensor [18] and 36dB for LF sensor [10]. For hits over 1 µs, the mean number of hits per rotation, hit amplitude and duration, time to peak of the hit (rise time), signal strength, and absolute energy were included in the age group comparison, based on the previous work [11], [19]. For the high amplitude hits, the overall number was considered.

B. Self-reported knee status

Additionally, the Knee Injury and Osteoarthritis Outcome Score (KOOS), a questionnaire that specifically targets symptoms and function in patients with knee injury and OA [20], was used to assess the self-reported condition of the participants' knees.

C. Statistical analysis

The statistical analysis of the data was performed using IBM SPSS Statistics v.28. Since, according to the previous work [11], [19], the AE parameter values were considered to be non-normally distributed, a Mann-Whitney U test was used to compare AEs between the OG and YG. A significance level of $p>0.05$ was used for all comparisons. Additionally, Spearman's coefficients were calculated to assess the correlation between age and AE parameters.

III. RESULTS

Due to equipment malfunction or erroneous recordings, twenty AE recordings out of 612 (approximately 3.3%) were missed or removed from the data analysis. Additionally, for participant 8 (record LF_1_60), only 33 repetitions were included, as the remainder of the repetitions did not fall within the required 1±0.2s. Similarly, for participant 22, only 38 repetitions were considered in the LF_3_60, LF_2_60, and HF_3_60 recordings.

A. YG and OG comparison

The mean and standard deviation, median, and interquartile ranges of the KOOS in the OG were 74.46 (14.71) and 75.5 (18) respectively. For the YG, the mean score was 92.64(7.51) and the median score was 96 (10). The values are presented in Figure 2. The results (p-values) from the comparisons of AE parameters between age groups are presented in Table III, with several differences being observed for the LF sensor.

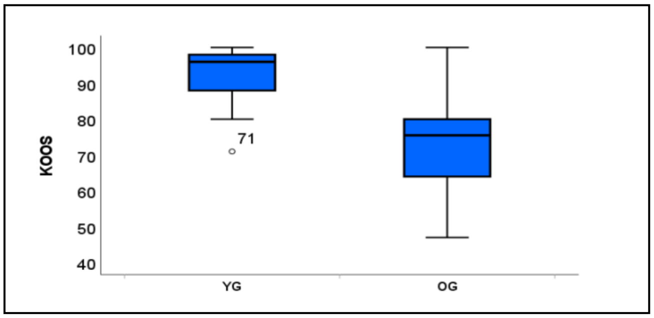

Figure 2. Boxplots of KOOS in OG and YG

TABLE III. COMPARISON OF AE PARAMETERS BETWEEN AGE GROUPS, P-VALUES

Mode	**hit amplitude, dB**	**Median hit duration, µs**	**Median hit rise time, µs**	**Median hit absolute energy, attoJoules**	**Median hit signal strength, pV-s**	**Mean number of hits per rotation**	**Number of hits over 32dB**	**Number of hits over 36dB**
LF_1_30	.061	**.014**	**.021**	**.014**	**.014**	.086	.062	**.041**
LF_2_30	.490	.604	.197	.462	.474	.088	.139	.207
LF_3_30	.100	.125	.072	**.032**	.050	.090	**.034**	**.026**
HF_1_30	.809	.238	.718	.718	.549	.796	.634	.569
HF_2_30	.790	.241	.256	.337	.269	.918	.951	.592
HF_3_30	.864	.680	.584	.570	.599	.635	.509	.563
LF_1_60	.594	.070	.071	.070	.070	.443	.299	.225
LF_2_60	.321	**.049**	.080	**.049**	**.041**	.377	.121	.118
LF_3_60	.325	.097	.193	.056	.068	.584	.951	.836
HF_1_60	.616	.638	.515	.826	.944	.682	.734	.984
HF_2_60	.515	.562	.834	.952	.960	.424	.968	.920
HF_3_60	.396	.256	.295	.290	.222	.479	.156	.317

p-values < 0.05 presented in **bold**

Specifically, for Mode 1 with a 30rpm cadence (LF_1_30), the median hit duration (*p*=0.014), rise time (*p*=0.021), absolute energy (*p*=0.014), signal strength (*p*=0.014) and number of hits over 36dB (*p*=0.041) were higher in the older group. For Mode 3, also with a 30 rpm cadence (LF_3_30), the median absolute energy (*p*=0.032) and number of hits over 32dB (*p*=0.034) and 36dB (*p*=0.026) were higher in the OG. Similarly, for Mode 2, 60 rpm (LF_2_60), the median hit duration (*p*=0.049), absolute energy (*p*=0.049) and signal strength (*p*=0.041) were higher in the OG. The median group values of the abovementioned parameters, as well as related test statistics and effect sizes [21] presented in Table IV. Figure 2 shows that OG contains a wide range of KOOS (47-100), including participants with none to mild complaints, such overlap with YG potentially contributes to the relatively small difference between groups (Table III-IV).

B. Correlation with age

When assessing the correlation of knee AEs with age, only three parameters in two modes exhibited a weak correlation with p<0.05. Specifically, duration for LF_2_60 with *r*=0.283, *p*=0.047 [-0.004 0.526], rise time for mode LF_3_30 with *r*=0.296, *p*=0.035 [0.014 0.535] and signal strength for LF_2_60 with *r*=0.287, *p*=0.044 [0.000 0.529].

IV. DISCUSSION

TABLE IV. GROUP MEDIANS OF AE PARAMETERS AND MANN-WHITNEY TEST STATISTICS

Mode	**Parameter**	**Group median YG (IQR)**	**Group median OG (IQR)**	**Mean rank YG**	**Mean rank OG**	**η^2 (effect size)**
LF_1_30	*Duration, μs*	38.0 (42.8)	67.0 (187.8)	20.80	31.00	0.118
LF_2_60		50.0 (167.3)	102.0 (97.0)	21.44	29.56	0.078
LF_1_30	*Rise time, μs*	14.0 (18.5)	34.0 (44.5)	21.12	30.69	0.104
LF_1_30	*Absolute energy, attoJoules*	1.72 (3.04)	4.72 (18.48)	20.80	31.00	0.118
LF_3_30		4.90 (24.20)	11.63 (27.14)	21.44	30.38	0.090
LF_2_60		2.11 (6.22)	4.45 (5.28)	21.44	29.56	0.078
LF_1_30	*Signal strength, pV-s*	631.35 (902.80)	1509.0 (4952.61)	20.80	31.00	0.118
LF_2_60		771.65 (2627.56)	1645.5 (1779.02)	21.28	29.72	0.084
LF_3_30	*Number of hits over 32dB*	95 (170)	175.5 (196)	21.50	30.33	0.088
LF_1_30	*Number of hits over 36dB*	28 (119)	78.5 (97)	21.66	30.17	0.082
LF_3_30		45 (148)	115 (136)	21.26	30.56	0.098

In agreement with the previously published literature [22], the results of this study show that joint AE monitoring can distinguish groups of different ages and potentially indicate changes in the knee's cartilage status. However, further insights are presented in this study. Specifically, the number of hits or the amplitude of hits are often utilized in joint AE monitoring [13], [23]; yet, based on this study's results (Table III), employing solely amplitude-related parameters may not be the optimal choice in characterizing age-related changes. Taking into account AE parameters that include the duration of the AE hit, such as absolute energy or signal strength, as well as temporal parameters such as hit duration, might better highlight differences in knee conditions. Overall, the LF sensor provided a better distinction between age groups. In particular, for Mode 1, low cadence, and LF sensor (LF_1_30) the observed *p*-values were less than 0.1 for all the investigated AE event parameters, with effect sizes up to 0.118 (Table IV).

Moreover, a weak correlation between AE parameters and age was found for only three parameters and record types, while a moderate correlation (up to 0.475) was observed with KOOS [24], indicating that changes in knee AEs are associated with pathological, rather than age-related physiological changes. This is also reflected in the groups' comparison, where the OG had lower KOOS and higher median values for several AE parameters (Table IV). This finding shows that AE monitoring can potentially be more indicative of pathological ageing (e.g. OA [1]) than physiological (e.g. cartilage thinning [25]).

As a limitation of the study, the analyzed sample was not limited to participants with clinically confirmed absence of OA or past knee injuries in both groups, thus containing a variety of self-reported scores and conditions. Future studies might include investigations within specific age groups with clinically confirmed conditions to identify the change in AEs.

V. CONCLUSION

The present study suggests AE hit definition parameters as well as AE sensor frequency range that provide better differentiation between age groups, allowing for further improvement of the joint AE monitoring. Moreover, the results indicate that changes in knee AEs may be more indicative of pathological changes than healthy ageing, suggesting the usefulness of joint AE monitoring in OA diagnosis.

APPENDIX

For Mode 1, the PDT was estimated using the sensor spacing distance divided by the speed of the AE wave in the material [6]. The wave speed was equated to the speed of sound in the cancellous bone (2140 m/s at 270 kHz [26]). The knee diameter was set as the sensor spacing distance, with an average of 77.2 mm [27]. The PDT was calculated and rounded to 40 μs. The HDT was estimated using the formula 20/AC, where AC is the attenuation coefficient (dB/mm), but it should be at least twice as long as the PDT [6]. The HDT was calculated and equal to 67.7μs with an AC of 295.324 dB/m at 270 kHz [26]. However, HDT was adjusted to 80μs to be at least twice the value of PDT [6]. To include reflections of the original wave in the recording, the HLT was set as short as feasible at 40μs.

ACKNOWLEDGMENT

The authors would like thank the participants for their time.

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