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研究課題名（和文）Adaptive AE Tomography technique for novel diagnosis of osteoarthritic knees by passive volumetric reconstruction algorithm

研究課題名（英文）Adaptive AE Tomography technique for novel diagnosis of osteoarthritic knees by passive volumetric reconstruction algorithm

研究代表者
KHAN　M. I.（KHAN, M. I.）

佐賀大学・理工学部・准教授

研究者番号：５０４２３６０３

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研究成果の概要（和文）：令和3年度では提案した関連実験を実施するために必要な実験装置を準備した。研究の基礎を明確し、代数的再構成(ART)に基づくAEトモグラフィ理論を考案した。令和4年度では明確にした理論の実証実験を行った。膝関節は非常に小さいので、より少ない数のセンサを利用してトモグラフィ画像の品質と精度を確認した。令和5年度では内部の損傷が評価できる高い精度のAEトモグラフィ研究装置の準備した。シミュレーション的な研究課題を出してAEトモグラフィ関連問題解決を高い精度で行った。この結果は、OA膝の早期の正確な検査にも利用できうる。全ての研究結果より査読論文，国際及び国内発表も行った。

研究成果の学術的意義や社会的意義
適応型AEトモグラフィ技術ではAE信号処理より新しい体積画像、特に膝関節内の軟骨損傷を可視化する。この研究の主な特徴は、膝を速度分布が変化する局所的に等方性の不均質媒体と見なしてAEトモグラフィ再構成技術を適用することである。現在のトモグラフィによる再構成は、OA膝の初期段階であってもその診断を行いうる。また、提案されたAEトモグラフィでは、動的に自己生成されたAE信号を使用するため、従来装置のように外部から放射線や高エネルギー信号を体に照射しない。従って、提案された技術は健康的に安全であり、OA膝の早期発見もできる。従って、高齢者の生活の質を向上させる上で重要な役割を果たす。

研究成果の概要（英文）：In FY2021, the equipment necessary to carry out tomography related experiments were prepared according to the proposed research. The theory of AE tomography based on algebraic reconstruction technique (ART) was developed. In FY2022, proof-of-concept experiments were conducted according to the clarified theory. As the periphery of knee joint is very small for the placement of large number of sensors. Therefore, a small number of sensors were provided to confirm the quality and accuracy of the tomographic images.In FY2023, a research device for AE tomography has developed with high accuracy which can evaluate internal damage like small area like knee joint. The AE tomography technology developed by setting up a simulation-like research topic was able to solve the problem with high accuracy. These results can also be used for early and accurate treatment of OA knees. All results are published in peer-reviewed journals and national, international conferences.

研究分野：工学

キーワード：適応型AEトモグラフィ技術　知能機械　人間機械システム　診断評価　膝関節炎症診断

１．研究開始当初の背景

Osteoarthritis (OA), a severe knee disease, is caused by the damage of articular cartilage at the end of anatomical structures conjugated to knee joint (Fig. 1). It disables people of all ages. Its prevalence is predicted to increase as a result of increasing ages. In worst cases of OA, joint replacement is needed with mixed satisfaction of patients.
A potential approach of reducing the impact of such knee disease is to begin its treatment in early stage. However, limited sensitivity and health hazard by ionizing radiation of presently using diagnosis techniques (X-Rays, CT, MRI etc.) refer their limited applications in clinical diagnosis. Therefore, as prevention, regular monitoring of knee integrity for early treatment of OA is not possible with presently available tools for diagnosis.

A noninvasive method based on acoustic emission (AE) technique for the analysis of OA knee has been developed and documented by the present researcher. Aging effects to OA and its existence are clarified by his developed technique. Since, no external energy is needed to insert into the knee, developed AE technique is safe and frequently applicable for regular inspection of the knee integrity. However, the complicated anatomy of knee joint makes the AE signal propagation field as heterogenic. Thus, accurate localization and characterization of damages in OA knees are not yet possible due to assuming the uniform propagations of AE waves inside the knee joint.

Therefore, special measures are taken in the proposed adaptive AE Tomography technique for novel diagnosis of osteoarthritic knees by passive volumetric reconstruction algorithm, where AE signals are considered propagations with locally varying wave speeds in adaptive modes, and thus, the present problems in accurate diagnosis of osteoarthritic knees have been solved.

２．研究の目的

The main Purpose of the proposed research is summarized as follows:
I. Development of an adaptive AE tomography technique for novel diagnosis of osteoarthritic knees based on passive volumetric reconstruction algorithm.
II. Applying the developed technique of volumetric adaptive AE tomography to accurate diagnosis of knee osteoarthritis, even in early stage of damages for removing the risk of disabling people, particularly, in an aging society.

３．研究の方法

According to the proposed plan, an adaptive AE Tomography technique for novel diagnosis of osteoarthritic knees by passive volumetric reconstruction algorithm has been developed. Algebraic reconstruction technique (ART) has been utilized for volumetric reconstruction in developed technique. AE simulated results on an aluminum block were analyzed for verifying the parametric characteristics of generated AE signals. The characteristics of osteoarthritic knees were visualized and compared according to the changes of lower limb muscles activities based on the aging as well. Damage properties of osteoarthritic knees were clustered by applying PCA algorithm for evaluating the integrity properties of knee joint. Tomography images were also verified with small number of AE sensors for the adaptive application of reconstruction techniques to osteoarthritic knees. Optimization by iterative reconstruction for volumetric imaging in 2-dimension and 3-dimension.

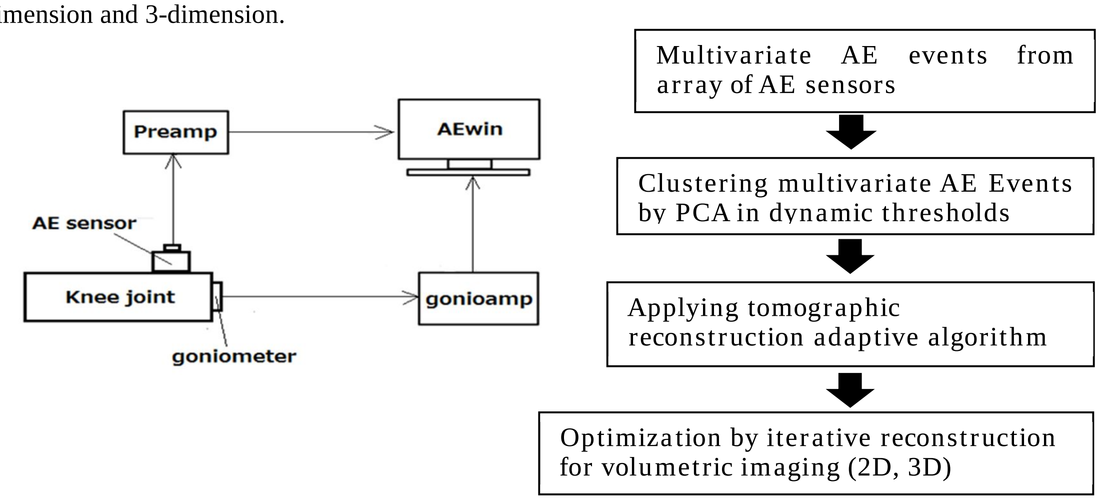

Fig. 1 Schematics and steps of Adaptive AE Tomography for volumetric imaging of OA knees.

4．研究成果

Results of Time of Arrival (TOA) detection for wave velocity identification experiments

Akaike's information criterion (AIC) method was used for picking the time of arrival (TOA) of the received AE signal. Accurate detection of TOA of AE wave is the key solution for AE tomographic imaging. Therefore modeling (for simulation) and experimental analysis of picking of TOA was conducted precisely. The well-known AIC was applied in calculating TOA in AE signals from array of AE sensors as sensor 1, 2, 3, etc. mentioned as S1, S2 and S3 with the increase of source to sensor distance, R. The TOA was determined from the data received by AEwin software for a threshold value of 40 dB. The experimental schematic and corresponding results are shown in Figs. 2 and 3 .

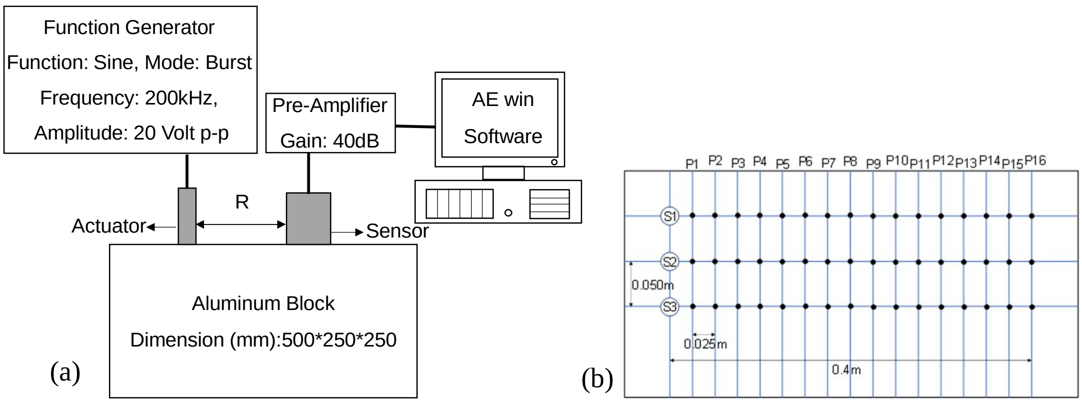

Fig. 2 (a) Schematics of the experimental setup (b) Positioning of sensors 1, 2, 3 on Aluminum block.)

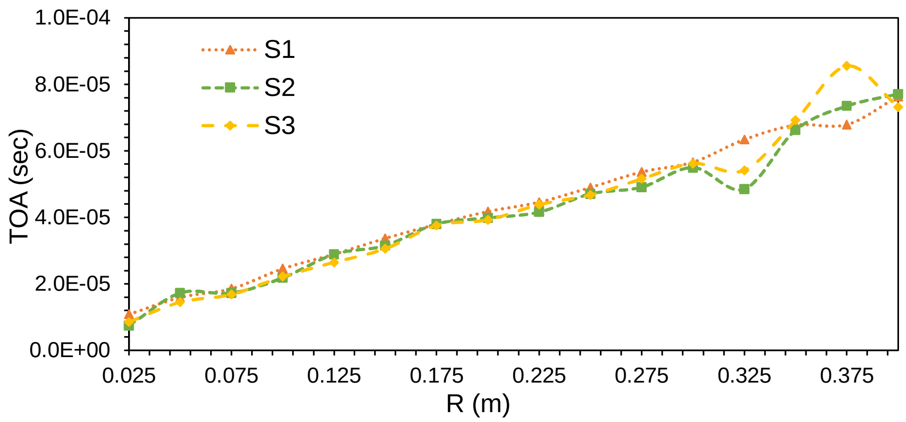

Fig. 3 The time of arrival (TOA) of the P-wave along S1, S2 and S3

Table 1 The wave velocities along S1, S2 and S3 directions

	Theoretical values	Experimental values			
		S1	S2	S3	Average
P wave velocity, (m/sec)	6189.7	5732.246	5330.734	5554.543	5539.174
R wave velocity, (m/sec)	2905.9	2014.401	2190.023	2213.515	2139.313
S wave velocity, (m/sec)	3117.9	2131.465	2338.95	2356.591	2275.668

Weve velocity was measured for detecting the slowness of wave propagation for AE tomography.

Characterization of OA knees compared with lower limb muscles activities based on aging

Short time Fourier transform (STFT) as a popular and powerful tool for extracting EMG signal features is used to establish an incredibly valuable class of time-frequency distributions that describe a complex amplitude versus frequency and time for signals taken from non-damaged knees (with young (A-group), middle aged (B-group), old (C-group) participants and OA-patients' (D-group) knees modeled from the following equation based on lower limb muscle activities (RF is shown in the figure).

$$\left.\begin{aligned} X_m(\omega) &= \sum_{n=-\infty}^{\infty} x(n)w(n-mR)e^{-j\omega n} \\ &= DTFT_{\omega}(x.SHIFTmR(w)) \end{aligned}\right\} \quad (1)$$

Where $x(n), w(n), X_m(\omega)$, and R are the input signal at instant n, window of length M, discrete time Fourier transform (DTFT) of windowed data with centered on the intervals of time mR and hope size between consecutive DTFTs respectively. The corresponding results are shown in Fig. 4.

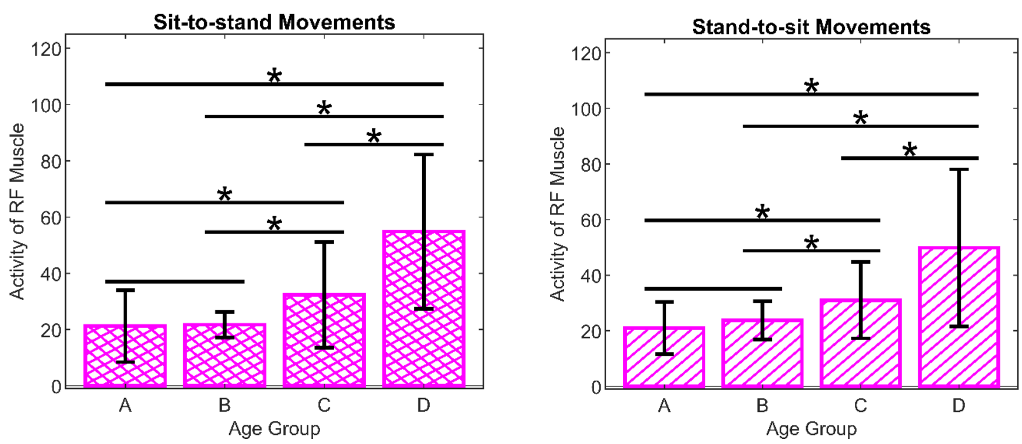

Fig. 4 RF Muscle activity showing ageing effects compared with OA knees at sit-to-stand (left) and stand-to-sit (right) movements. B, C groups' results show the early damage conditions of knee joint.

Results of Gaussian mixture model (GMM) Cluster of AE signals from Knee Joints

By applying GMM clustering, knee damages due to aging and OA are clarified for clear understanding of AE signals approach. Results in Fig. 5 accurately clarify the parametric signal's characters distribution accordingly.

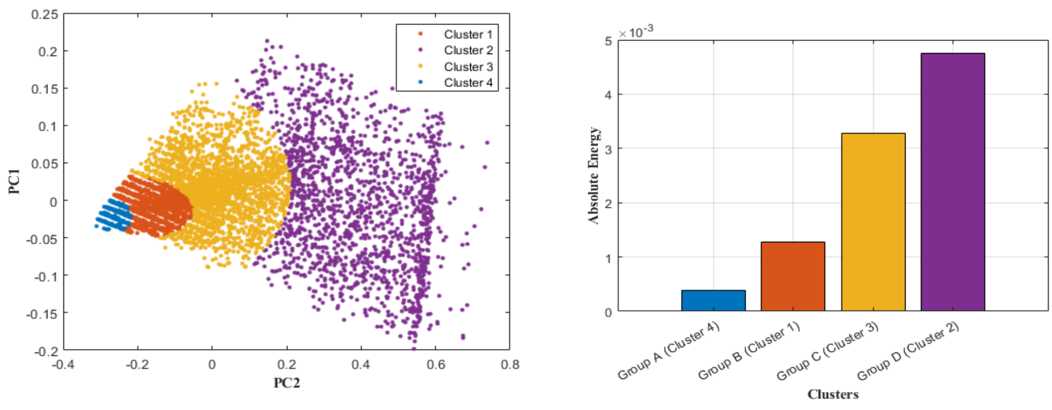

Fig. 5 Average value distribution based on absolute energy of AE signals from Knee joints.

Adaptive acoustic emission tomographic imaging in damage detection

The arrival times of each AE event at all sensors have been recorded in the experiment. These recorded arrival times were served as the input data for the subsequent AE tomography analysis. The AIC technique calculated the arrival time for each sensor. Following the simulation, the results for numerous AE events were obtained. These results were then utilized to compute the slowness of AE wave propagation at each PLB test. The results depict a single damage scenario in Fig. 6. Notably, the ray tracing calculations for this slowness mapping, disregarded the ray path through the damage zone, since the AE signals travelled a longer distance due to the effect of the defect. Thus, this adaptive AE tomography technique has been made ready for the application of volumetric imaging of cartilage damages in OA knees.

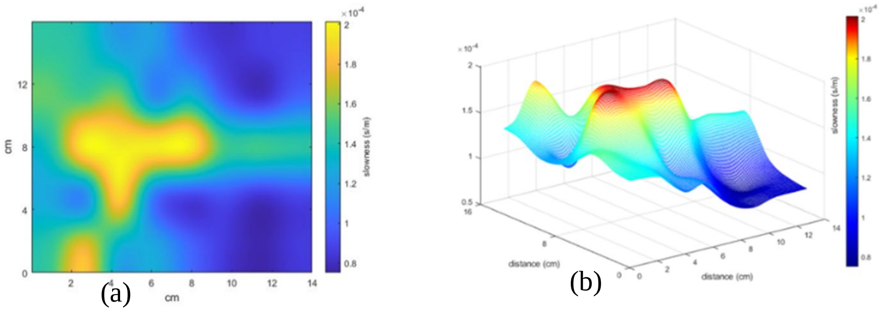

Fig. 6 Tomographic mapping of slowness in a damaged sample area, (a) 2D image, (b) 3D image

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　4件／うちオープンアクセス　4件）

１．著者名 Tawhidul Islam Khan, Nazmush Sakib, Md. Mehedi Hassan, Shuya Ide	４．巻 87
２．論文標題 Gaussian mixture model in clustering acoustic emission signals for characterizing osteoarthritic knees	５．発行年 2023年
３．雑誌名 Biomedical Signal Processing and Control (Elsevier Journal)	６．最初と最後の頁 1，10
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.bspc.2023.105510	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 Arif Abdullah Rashid, Md. Tawhidul Islam Khan and Kenbu Teramoto	４．巻 Vol. 28, No. 1
２．論文標題 Modeling of Acoustic Emission Wave and Its Parametric Characterization Based on Peak Sensor Sensitivity on an Aluminum Block	５．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.20855/ijav.2023.28.11900	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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２．論文標題 Analysis of Ageing Effect on Lower Limb Muscle Activity using Short Time Fourier Transform and Wavelet Decomposition of Electromyography Signal	５．発行年 2023年
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掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.sbsr.2023.100550	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

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3．学会等名 29th International Congress on Sound and Vibration, Prague, Czech Republic（国際学会）
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２．発表標題 Acoustic Emission Features in Characterizing Osteoarthritic Knees by Applying Unsupervised Machine Learning Algorithm
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〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

8．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関