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Motion Artifact Resistant Mounting of Acoustic Emission Sensors for Knee Joint Monitoring

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***Abstract*— Among the many diverse methods of recording biological signals, sound and acoustic emission monitoring are becoming popular for data acquisition; however, these sensors tend to be very susceptible to motion artefacts and noise. In the case of joint monitoring, this issue is even more significant, considering that joint sounds are recorded during limb movements to establish joint health and performance. This paper investigates different sensor attachment methods for acoustic emission monitoring of the knee, which could lead to reduced motion and skin movement artefacts and improve the quality of sensory data sets. As a proof-of-concept study, several methods were tested over a range of exercises to evaluate noise resistance and signal quality. The signals least affected by motion artefacts were recorded when using high-density ethylene-vinyl acetate (EVA) foam holders, attached to the skin with double-sided biocompatible adhesive tape. Securing and isolating the connecting cable with foam is also recommended to avoid noise due to the cable movement.**

***Clinical Relevance*— The results of this study will be useful in joint AE monitoring, as well as in other methods of body sound recording that involve the mounting of relatively heavy sensors, such as phonocardiography and respiratory monitoring.**

***Keywords*— acoustic emission, on-body sensor monitoring, motion artifacts, sensor attachment, joint sounds**

I. Introduction

Acoustic emission (AE) monitoring is a method of non-destructive testing, widely used for defect detection in a broad range of materials, including metals, plastics, polymers, concrete, and wood [1]. AE monitoring is based on the recording and analysis of transient elastic waves generated within a material or structure due to the rapid release of energy from localized sources [2]. AE signals may originate from mechanical or phase transformations in the material under test, as well as corrosion, friction, and magnetic processes within the material [3]. The most commonly used technique in AE monitoring is the registration of AE signals that exceed a pre-set or a floating amplitude threshold. Such occurrences are generally referred to as hits. Apart from the selection of the threshold, several other parameters (Fig. 1) are used in the determination of hits; for example, hit definition time (HDT) specifies the maximum time between threshold crossings, hit lockout time (HLT) defines the time that must pass after a hit has been detected and before the next one occurs, and peak definition time (PDT) determines the time from hit to peak detection [4]. Additionally, number of hits, duration, rise and fall times, and measured area under the rectified signal envelope (MARSE) are often used in signal analysis.

The first works on the use of AE monitoring in orthopedics appeared in the late sixties with the analysis of bone breaks and ligament tears [6]. However, considering the non-invasive nature and low cost of AE monitoring, this method can be employed in diagnostics of deteriorative joint conditions as was confirmed by recent investigations [6]. Examples include identification of joint conditions such as osteoarthritis [7], [8], age-related joint deterioration [9], meniscal injury and surgery [10], and past knee injury or joint pain [11]. However, the majority of the published works are proof-of-concept studies, and an in-depth look into the applicability of the technique in clinical settings is needed.

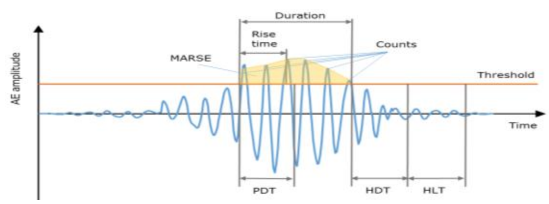

Figure 1. Parameters of AE signal.

Considering the types of sensors used for AE and their associated mounting methods, contact sensors with coupling gels have been most often used since they better facilitate the acoustic signal transition from skin surface to sensor [6]. The majority of the works also use tape or straps to secure the sensor in the desired position; however, such attachments can themselves generate acoustic emissions when deforming during movement of the body part under analysis. Considering the impact of sensor fixation in obtaining an acoustic signal of good quality from skin contact sensors, little research has been conducted on the potential adverse effects of improper fixation or how to address it [6]. To the best of the authors' knowledge, only the work by Ozmen et al. [12] specifically discusses sensor mounting for joint sound recording; however, motion artefacts and skin movement have yet to be considered in detail. The goal of this proof-of-concept study is therefore to investigate the effects of sensor mounting on the quality of recorded signal, and propose a solution that minimizes noise and motion artifact influence.

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II. METHODS

For this proof-of-concept study, two volunteers were recruited (females, 164/163 cm and 60/58 kg) with no record of musculoskeletal, skin or other disorders. The study was conducted according to the criteria set by the declaration of Helsinki and approved by the Clinical Research Ethics committee of the Cork Teaching Hospitals. Informed consent and Physical Activity Readiness Questionnaire (PAR-Q) were also obtained.

Knee joint AEs were recorded using the USB AE Node monitoring system (Physical Acoustics) and a medium frequency AE sensor with a preamplifier (PK151). The sensor weights 51 gr, and has a height of 27 mm and a diameter of 20.6 mm. The device was attached on the medial tibial condyle area, as it showed the minimum muscular and dynamic artifacts in AE event acquisitions in osteoarthritis analysis [9]. AE hit parameters were pre-set (PDT: 200 μs, HDT: 800μs, HLT: 1,000 μs), with a registration threshold equal to 32 dB (around 40 μV) and a frequency range of 20-500 kHz. The choice of hit definition parameters and frequency range was based on the results of Shark et al. [13] as they were successfully used to differentiate healthy and OA knees. Additionally, custom inertial motion capture sensors were placed on the shank and thigh of the participants, as well as on the crank of the stationary bicycle that was used for cycling. Methods of sensor mounting were evaluated during two types of exercises. The first group included straight leg hip flexion / extension (SLF) and straight leg hip abduction / adduction (SLA). These exercises include motion of the straight leg in either the sagittal or frontal planes and were assumed to produce little to no AEs from the knee as they do not involve any bending or loading of the joint. The second category of exercises included movements with knee movement, such as single-leg squats (SLS), knee lifts (KL), and cycling. Ten repetitions of each exercise were executed in random order. A metronome (20 bpm) was used to assist in periodic exercise execution. Testing was continued with cycling on a stationary bike with two cadences (30 and 60 rpm), and the lowest (L) and highest (H) available loads to provide loading in a controlled manner. To ensure stable cadence during exercise execution, the metronome and a cadence sensor connected to a smartphone were used to assist the participant with audible and visual feedback. All four cycling modes (L30, H30, L60, H60) were recorded for a minute each. The order of modes was randomized as well. Several methods of sensor attachment were considered (described below), and each volunteer repeated the test three times over the course of several days.

A. *Foam holders: size and foam density*

Investigated parameters for the attachments included the foam holder presence and its size (no foam, small holder with 4.5 cm Ø, and large with 5.5 cm Ø and height of 1.8 cm in both cases with an indentation for the cable), and densities: low (cross-linked polyethylene - XPE, 25 kg/m3) and high (ethylene-vinyl acetate - EVA, 100 kg/m3). Holder diameters were chosen by taking into account the knee area and curve, while also ensuring sufficient adhesion surface to safely secure the sensor. Examples are shown in Fig. 2. The sensor was tightly fitted in a holder so the sensing surface was slightly protruding (1 mm) to provide a good acoustic interface to the knee. A similarly shaped holder (although the type of foam was not indicated) with additional nylon housing has been previously used in hip joint sound recordings [14], however its impact on AE signal acquisition has not been reported.

Figure 2. Foam holders left to right: low density / 5.5cm Ø, high density / 5.5cm Ø, low density / 4.5cm Ø, high density / 4.5cm Ø.

B. *Adhesion and cable fixation*

Preliminary trials revealed that while double-sided sticky tape provides good adhesion to defatted and dry skin, the contact interface between the foam holder and the tape was unstable. This led to the foam holder containing the sensor slowly unsticking from the tape during cyclic movements, resulting in noisier recordings, and interruptions in the data collection. However, the thin layer of contact glue that was applied on the foam surface led to significantly improved adhesion at the foam and the tape interface, and thus, less noisy recordings. Cable fixation with only tape did not provide full noise isolation from cable movements during exercise execution. The graph below shows the signal characteristics (hits and energy) that was recorded while a small amplitude swinging motion was imparted on the cable, while the participant was not moving (Fig. 3, left). Securing the cabling with foam (Fig. 3, right), instead, provided recordings that were free from the noise caused by cable movements.

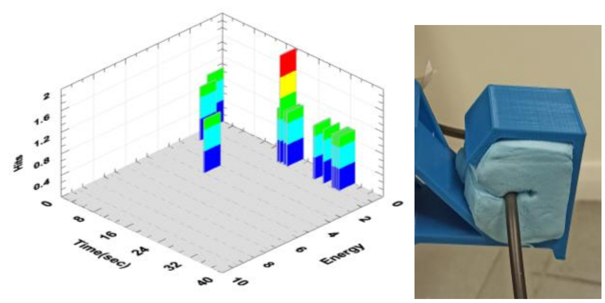

Figure 3. Noise due to cable movement and proposed cable fixation.

Thus, a thin layer of flexible contact glue (MS Polymer) was applied to the foam's surface, and after drying, it was tested along with a double-sided tape in an effort to improve adhesion between foam and tape. Double-sided bio-compatible sticky tape was used to attach the sensors and holder to the dry, defatted skin. Additionally, cables were secured to the lower leg either with medical tape alone or were covered by foam and additionally secured with tape. Table I summarizes all the investigated types of attachment.

TABLE I. ATTACHMENT TYPES

Trials	Mounting	Cable fixation	Adhesion
Preliminary	1. No holder 2. 5.5 cm, soft 3. 5.5 cm, dense	1. Free cable, medical tape 2. Desk holder, medical tape, foam insulation	1. Double-sided tape 2. Double-sided tape + glue priming of the hoder foam
Main	1. 4.5 cm, soft 2. 4.5 cm, dense	1. Desk holder, medical tape, foam insulation	1. Double-sided tape + glue priming of the hoder foam

C. Data processing

AE recordings were obtained using the AEwin software. Both AE and motion capture files were exported as ASCII files and further analysed in MATLAB. AE records were firstly synchronized with motion data with the use of time-stamps. For the non-cycling exercises, eight repetitions were analysed, with the first and last repetitions excluded due to additional noise and/or compromised execution in some cases due to foot contact with the floor. For cycling, 40 rotations were included in the analysis of the 60 rpm trials and 20 rotations for the 30 rpm. The mean number of hits per rotation and median absolute energy of hits were extracted. Absolute energy was derived from the integral of the squared voltage signal divided by the reference resistance over the duration of the AE waveform packet. As a time-driven feature, this is a suitable parameter for monitoring continuous signals, as it is independent from hit-based activity [15]. Thus, by using absolute energy and hits, both hit-related and time-related signal characteristics were evaluated. The median value of the absolute energy was chosen to minimize the effect of outliers to which this parameter is particularly sensitive.

III. RESULTS AND DISCUSSION

The fixation with only double-sided tape and no holder showed unsatisfactory results. The sensor was prone to uncontrolled movement and the adhesion surface was not sufficient to hold it in place. Tape unsticking and sensor movement resulted in large discrepancies in signal characteristics even over the duration of a single exercise. Fig. 4 shows an example of the increased noise after 30 s of cycling, due to partial adhesion of the sensor.

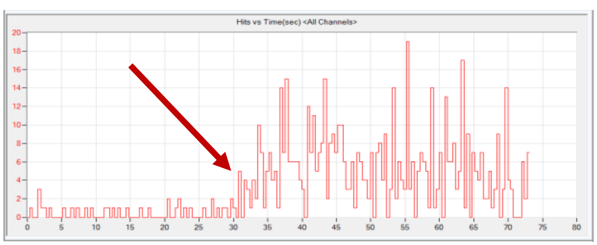

Figure 4. Elevated noise (in hits per sec) due to the unsticking tape.

Two out of three trials with a larger size foam holder used for the first participant resulted in the holders unsticking from the skin during either knee flexion, squats or cycling (Fig. 5, left). Both low and high-density foams were prone to this particular issue. Smaller foam holders provided better adhesion in all tested exercises. Further trials focused on investigating the updated fixation: smaller holders, foam isolated cabling with fixed excess, and coating the foams' surface with glue for improved adhesion (Fig. 5, right).

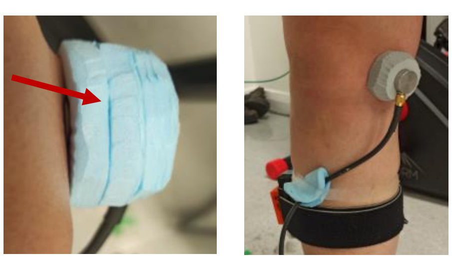

Figure 5. Holder unsticking (left), and proposed fixation (right)

A. Foam density

The signal characteristics (average values for each of the three trials) are presented in Tables II and III. The low-density foam holder, however, did not prevent the movement of the sensor, especially in the sagittal plane, thus resulting in elevated noise levels during hip flexion (SLR, Table II and III). In all cases, the number of hits per repetition for non-knee bending exercises was less than one. Overall, the high-density foam holders provided signal recordings with a lower discrepancy between trials, which is more noticeable in the time-related absolute energy values in comparison with the lower density foam holders (Table III), particularly in high intensity exercises such as cycling. Signals obtained using a sensor enclosed with a dense foam holder have comparatively higher amplitudes (more hits detected) than when soft foam holders for exercises with knee flexion, similarly to the mounting methods with and without 3D printed backing in [12]. Isolated high amplitude events (high absolute energy) were observed for both participants (third trial). Those outliers only happened during SLF and SLA (Table III) and not during cycling or squatting, and coincide with the minimal hip angle, which suggests accidental hitting of the sensor with the opposite leg.

TABLE II. SIGNAL PARAMETERS: HITS PER REPETITION

Exercise	**Low density foam, 4.5cm**					
	Hits per cycle (SD)					
	Participant 1			***Participant 2***		
	Test 1	**Test 2**	**Test 3**	**Test 1**	**Test 2**	**Test 3**
SLF	0	2.3 (1.0)	0.4 (1,1)	1 (1.2)	0	0.3 (0.7)
SLA	3.0 (1.8)	0.6 (0.7)	0.1 (0.4)	0	0	0
KL	1.5 (1.19)	1.8 (0.9)	3.8 (1.6)	1.5 (0.9)	1.4 (1.5)	3 (2.3)
SLS	7.5 (2.9)	6.6 (2.3)	4.0 (2.3)	5.9 (2.17)	4.1 (2.6)	4.1 (1.2)
L30	4.6 (1.1)	12.7 (2.0)	5.4 (2.3)	8.9 (1.4)	4.3 (1.7)	2.5 (0.7)
H30	4.6 (1.4)	12.7 (1.8)	4.6 (2.0)	11.3 (1.6)	5.0 (1.7)	5.6 (1.1)
L60	5.4 (1,7)	11.7 (3.2)	5.5 (1.8)	6.8 (2.3)	8.0 (1.6)	4.2 (1.0)
H60	5.9 (1.9)	20.0 (3.1)	6.9 (1,7)	9.9 (1.6)	4.8 (1.6)	5.2 (1.0)
	High density foam, 4.5 cm					
SLF	0	0	0	0.3 (0.7)	0	0.3 (0.5)
SLA	0	0.4 (0.7)	0.25*	0	0.1 (0.4)	0.1 (0.4)
KL	11.4 (3.1)	15.5 (4.0)	9.6 (2.0)	0.5 (0.8)	8 (2.3)	18.1 (2.0)
SLS	21.8 (4.1)	13.5 (2.0)	10.5 (4.0)	2.5 (1.3)	15.9 (3.9)	9.8 (2.5)
L30	37.5 (4.1)	13.3 (2.7)	15.5 (2.5)	9.7 (1.5)	26.2 (7.0)	31.8 (4.3)
H30	48.1 (3.6)	14.3 (2.7)	20.5 (1.3)	12.4 (1.6)	20.6 (2.0)	33.4 (3.9)
L60	47.4 (2.9)	26.0 (2.7)	27.8 (2.3)	15.5 (2.5)	24.7 (2.9)	25.9 (3.3)
H60	44.8 (3.9)	24.3 (2.1)	22.7 (2.3)	14.0 (2.0)	20.7 (2.8)	44.7 (3.1)

SLF – straight leg flexion, SLA – straight leg abduction, KL – knee lift, SLS – single leg squat, L30 – low load, 30 rpm cycling, H30 – high load, 30 rpm cycling, L60 – low load, 60 rpm cycling, H60 – high load, 60 rpm cadence cycling.

TABLE III. SIGNAL PARAMETERS: ABSOLUTE ENERGY

Exercise	**Low density foam, 4.5cm**					
	Median absolute energy					
	Participant 1			***Participant 2***		
	1	**2**	**3**	**1**	**2**	**3**
SLF	18.94	4.57	1.27	13.52	0	9.43
SLA	0	8.36	2.61	0	0	0
KL	1.44	34.66	19.51	4.13	0.19	41.75
SLS	4.35	55.58	11.45	2.54	2.94	3.27
L30	5.37	16.95	6.56	36.25	10.06	15.44
H30	13.27	22.41	4.85	20.04	13.55	36.16
L60	11.07	15.70	7.77	24.18	24.01	65.05
H60	7.17	18.97	9.85	23.69	23.86	80.59
	High density foam, 4.5 cm					
SLF	0	0	0	13.28	0	110.1*
SLA	0	2.07	591.1*	0	32.58	42.52
KL	12.77	13.50	6.24	0.2	9.26	26.83
SLS	9.70	23.35	10.34	0.65	15.96	11.54
L30	11.23	13.16	11.6	27.85	15.03	24.84
H30	11.60	17.90	9.82	12.41	13.30	18.15
L60	15.58	12.85	8.87	13.30	10.90	25.87
H60	15.16	18.03	12.03	13.64	11.08	18.96

SLF – straight leg flexion, SLA – straight leg abduction, KL – knee lift, SLS – single leg squat, L30 – low load, 30 rpm cycling, H30 – high load, 30 rpm cycling, L60 – low load, 60 rpm cycling, H60 – high load, 60 rpm cadence cycling.
*High energy outlier.

The holder that produced the most robust fixation, external noise isolation and little to no noise during straight leg movements, was the high-density EVA foam holder with a diameter of 4.5 cm. The cable was attached to the leg using medical tape and was additionally isolated with low-density foam. The excess cable was secured using a 3D printed cable holder with foam isolation (Fig. 3, right). A thin glue layer was added on the foam surface to improve tape and foam adhesion.

IV. CONCLUSION

AE monitoring of knee joint sounds is extremely sensitive to friction noise and motion artifacts, and fixation plays an important part in achieving repeatable results. In this proof-of-concept study, we investigated different components of sensor mounting and proposed methods to improve motion artifact resistance. Using foam isolation and holders, as well as ensuring good sensor adhesion to the skin, helps improve signal quality and ensure better repeatability.

The present study has some limitations that should be considered when interpreting the results. While potentially useful in a wide range of sensors, different mountings were tested on a sensor with specific measurements and weight, and in a predetermined frequency range. Another limitation of this work is the small range of used foam shapes and materials. The number of recorded trials has also potentially influenced the possibility of noticing minor differences between mounting methods. Considering the short exercise time and light load, the effect of perspiration on the sensor adhesion was not considered. Detection of high-energy outliers during specific exercises indicates that better control over exercise execution is needed, or evaluation should only be performed on the closed chain exercises. Observed test-retest variability might be observed due slight changes in the recording procedure (e.g., sensor placement) or the natural changes in the knee state over time. To further investigate the applicability of this method, both healthy and patient subjects with specific joint conditions should be assessed.

Future works include trials with multiple healthy volunteers to assess the reliability of using AE monitoring for the knee joint. Thus, we plan to assess the test-retest reliability of the method as well as the variability in the AEs of the knee joint, within a healthy control group.

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