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Mechanotendography: description and evaluation of a novel method for investigating the physiological mechanical oscillations of tendons using a piezo-based measurement system

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Abstract

The mechanotendography (MTG) is a method for analyzing the mechanical oscillations of tendons during muscular actions. The aim of this investigation was to evaluate the technical reliability of a piezo-based measurement system used for MTG. The reliability measurements were performed by using audio samples played by a subwoofer. The thereby generated pressure waves were recorded by a piezo-based measurement system. An audio of 40 Hz sine oscillations and four different formerly in vivo recorded MTG-signals were converted into audio files and were used as test signals. Five trials with each audio were performed and one audio was used for repetition trials on another day. The signals' correlation was estimated by Spearman (MCC) and intraclass correlation coefficients (ICC(3,1)), Cronbach's alpha (CA) and by mean distances (MD). All parameters were compared between repetition and randomized matched signals. The repetition trials show high correlations (MCC: 0.86 ± 0.13 , ICC: 0.89 ± 0.12 , CA: 0.98 ± 0.03), low MD ($0.03 \pm 0.03V$) and differ significantly from the randomized matched signals (MCC: 0.15 ± 0.10 , ICC: 0.17 ± 0.09 , CA: 0.37 ± 0.16 , MD: $0.19 \pm 0.01V$) ($p = 0.001 - 0.043$). This speaks for an excellent reliability of the measurement system. Presuming the skin above superficial tendons oscillates adequately, we estimate this tool as valid for the application in musculoskeletal system.

Key Words: mechanotendography; tendons; mechanical tendinous oscillations; piezo-based measurement system.

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The motor output is mostly examined by electromyography (EMG) and meanwhile also by mechanomyography (MMG). It is common knowledge that muscle fibers are mechanically oscillating in a stochastic way in low frequency ranges ~ 10 Hz.¹⁻³ The muscles function as actuators of the musculoskeletal system, which are mostly linked to the bones by tendons. Tendons are passive connective tissue structures, which are driven by the active parts. The force during movement is transmitted from muscles via aponeurosis and tendons to the skeleton.⁴ Thereby tendons transmit great forces, e.g., Achilles tendons are strained with about 9000 N during running.⁵⁻⁷ In basic research concerning tendons the distinct structures of tendons with different physiological requirements regarding their function^{8,9} or the modelling as well as linear and non-linear analysis of the mechanics of tendons are investigated.¹⁰ Clinical examinations in humans are usually performed by ultrasound to clarify the anatomical

structure or changes of them.^{11,12} Real-time ultrasound allows a scanning of the tendon during isometric contraction¹³⁻¹⁷ with the focus on force-displacement,¹³ deformation and stiffness¹⁵ to get information about the tendon's stress and strain.¹⁴ An oscillatory displacement of the tendon is not considered thereby. The oscillations of tendons generated during muscular force transmission are referred to as tendinous output, which is rarely investigated. The low sampling rate of 25 Hz used for real-time ultrasound¹⁵ are too low for analyzing tendinous oscillations. Established methods as MMG and EMG, respectively, only provide information about muscles, not about the passive structures. However, these passive structures often develop complaints as, e.g., tendinopathies. Since a change of motor control is inter alia discussed as potential factor for the development of tendinopathies,^{7,14,18-21} it would be of special interest to investigate the mechanical oscillating behavior of tendons, which are generated by muscles. Recordings of

tendinous oscillations might provide further insights than only capture the muscular activity, since tendons often reflect the oscillations of more than one muscle, e.g., the Achilles tendon, in which three muscle heads insert. It also might reveal more information than looking at the mechanical tendinous structure (fiber structure, thickness, stiffness, displacement, strain), since it includes the oscillatory behavior, which is generated by the neuromuscular system. Therefore, the recording of tendinous oscillations during motor actions might provide a more functional insight into the properties of tendons.

Recently, the tendon shear waves were assessed using high frame rate ultrasound, accelerometers or laser Doppler vibrometry after tapping on or shaking the tendon.^{22–25} The main finding of Salman²⁴ was that with increasing contraction the tendon stiffness increased. Martin et al.²² investigated the spread wave of the Achilles tendon using two accelerometers after tapping on the tendon during cyclic isometric ankle plantar flexion and during walking. Due to the change of shear wave in different gait phases they draw the conclusion, e.g., about the tendon's passive stretch.²² This is close to an investigation in which a myotonometer is used to apply a mechanical impact on the tendon and to record the resulting oscillation of the tissue in relaxed tendons.²⁵ This technique is quite similar to the Supersonic shear imaging (SSI), which also generates vibrations of tissue (using ultrasonic beams) and examines the shear wave of the tissue afterwards.²⁶ In all those investigations vibrations of the tendon are induced from external to measure the resulting shear waves with different techniques. However, when active, the muscles tighten the tendon. In this process, the muscles produce stochastically distributed mechanical oscillations, which can be measured via dynamometry and kinematics also without applying an external vibration or tapping.^{3,27,28} The oscillations work in axial direction along the tendinous strand. Thereby, the muscles act as actuators stimulating the passive tendon longitudinally and laterally. As far as we have assessed, no other research group recorded those oscillations of the tendon during muscular activity. Only a combination of muscle action and application of mechanical vibrations or tapping on the tendon are regarded, whereby especially the evoked shear wave was of interest so far. However, the oscillations of tendons during isometric muscle action can be detected by a piezoelectric sensor-based measurement system, which will be presented here. We estimate this technique as unique and innovative and suggest naming this method mechanotendography (MTG). It can be considered as analogy to MMG just applied for tendons.^{3,27,29}

Because of the novelty of this method using a piezo-based measurement system, there is the need of evaluation. The measurement system is adopted from music. The piezoelectric sensors and amplifiers are usually used to pick up and amplify auditory signals from

instruments. Thereby, they have been proofed to be suitable to take off harmonic oscillations. Anyway, the justifiable question remains if piezoelectric sensors are suitable to record stochastically distributed mechanical oscillations in low frequency areas ~ 20 Hz. The aim of this setting was to investigate whether this measurement system is able to capture those low frequency oscillations in a reliable way in a pure technical setting (ex vivo). The basic applicability of MTG in vivo was already shown in several publications. MTG and MMG of the triceps brachii muscle and tendon are, e.g., able to generate coherent behavior during isometric muscle action of the elbow extensors.^{3,27} Furthermore, MTG was applied in an investigation of patients with Achilles tendinopathy.³⁰

Materials and Methods

Piezoelectric sensor and amplifier used for MTG

A large number of piezoelectric sensors were tested for the use of recording the mechanical oscillations of tendons and muscles in the Potsdam Neuromechanics laboratory (Germany). Instrumental pickups are used to convert mechanical vibrations of solid objects into electrical voltage, which results in audio signals in the usual application. Mechanical pressure or structure-borne sound generate an electric voltage, e.g., in wind instruments. Considering the tendon as string, the structure-borne sound generated by the tendinous swing can be recorded by piezoelectric pickups. However, not

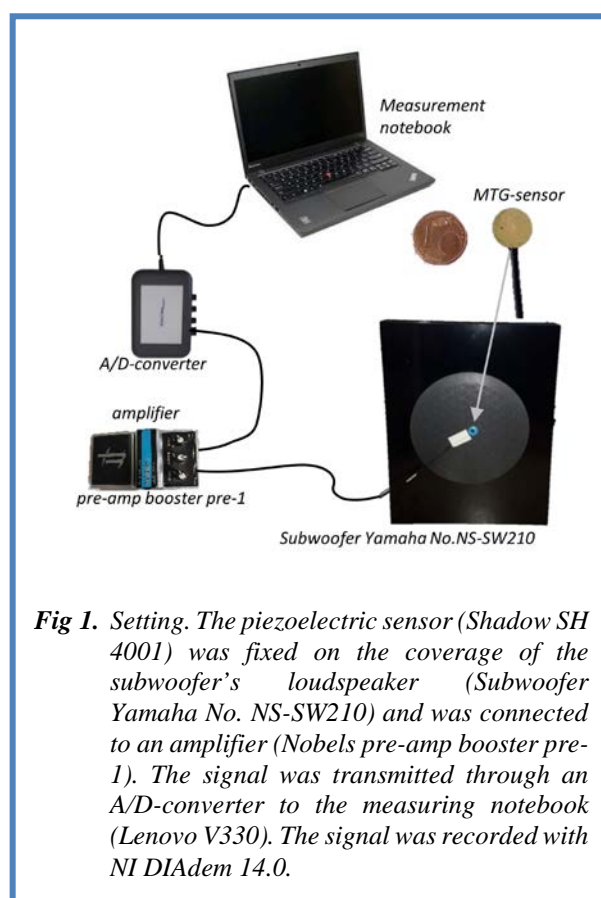


Fig 1. Setting. The piezoelectric sensor (Shadow SH 4001) was fixed on the coverage of the subwoofer's loudspeaker (Subwoofer Yamaha No. NS-SW210) and was connected to an amplifier (Nobels pre-amp booster pre-1). The signal was transmitted through an A/D-converter to the measuring notebook (Lenovo V330). The signal was recorded with NI DAQmx 14.0.

every pickup is applicable. Two pickups have been proven to be suitable to identify the mechanical oscillations of muscle-tendon structures: Shadow SH 4001 (pickup for clarinets and saxophones) and the Shadow SH-SV1 (pickup for violins). For the present investigation, the piezoelectric sensor Shadow SH 4001 was used to verify the reliability of those sensors (in the following called MTG-sensor). One benefit of those sensors is the small size ($\varnothing 12\text{mm}$) (Figure 1). Furthermore, the choice of an appropriate amplifier is essential. For MMG/MTG it must be suitable to amplify low-frequency ranges below 30 Hz. The guitar amplifier Nobels pre-amp booster pre-1 turned out to be applicable.

Setting and procedure

To examine the reliability of the piezo-based measurement system *ex vivo*, different audio samples (origin see below) were played by the Software NI DIAdem 2017 (National Instruments) via a subwoofer. The subwoofer Yamaha No. NS-SW210 Advanced YST II was used to generate mechanical pressure waves, which were picked up by the MTG-sensor. The subwoofer has a frequency response from 30 to 160 Hz and, therefore, appears to be just appropriate to reflect low frequency ranges. The MTG-sensor was fixed by special ECG-tape onto the coverage of the subwoofer's loudspeaker, where the pressure waves should be the highest (Figure 1). This same fixation is also used for measurements *in vivo*. The picked-up signal was amplified by Nobels preamp booster pre-1 and was transferred via A/D-converter (NI USB-6218, 16-bit) to the measuring notebook and recorded by NI DIAdem 14.0. Sampling rate was set at 1000 Hz.

Five different audio samples were used. Thereof, four formerly *in vivo* recorded MTG-signals were converted into audio samples to produce signals close to real applications: three audio samples from *in vivo* recorded MTG-signals of the Achilles tendon after impact³⁰ (audioMTGAchilles_1, audioMTGAchilles_2, audioMTGAchilles_3) and one MTG-signal from the triceps brachii tendon during isometric muscle action of triceps brachii muscle at an intensity of 80% of the MVC (audioMTGtri).³ The settings of the *in vivo* captured signals can be looked up in Schaefer & Bittmann^{3,30} including the approvals of ethics committee (University of Potsdam, Germany; no. 37/2015, 64/2016) and informed written consent of all participants. The fifth audio sample was a 40 Hz sine oscillation produced by an online tone generator (audioMTG40Hz) used to get further information concerning the amplitude and frequency reproducibility of the MTG-system.

To examine trial-to-trial reliability, five repetitions of each audio sample were played and recorded at the same day. The audioMTGAchilles_1 was re-recorded one day later (5 trials) to investigate the day-to-day reliability. To evaluate the objectivity and validity, the audio of 40 Hz sine oscillations was used.

Data processing and statistical analysis

The measured parameter was the amplified voltage of the piezoelectric sensor gathered from the mechanical oscillations of the subwoofer during audio replay (*ex vivo*). The raw data of each curve were used for data evaluation. Each recorded MTG-signal was cut into a short interval of 0.1s (MTGAchilles) and 0.5s (MTGtri, 40 Hz sine), respectively, using NI DIAdem 2017. The 0.1s interval of audioMTGAchilles was chosen because the original MTG-signal was recorded during a short impact on the forefoot of the participant from plantar in direction of dorsiflexion, which generated the here relevant oscillation of the Achilles tendon in the 0.1s interval after impact.³⁰ The MTGtri-signal was originally recorded *in vivo* during a 10s isometric muscular interaction of two participants.³ Since the sampling rate was 1000 Hz, 0.5s provide a sufficient long signal for the investigation of reliability.

To investigate the reproducibility the repetition trials of each audio sample were analysed by the following parameters: i) the mean distances of all data points between the curves (MD) (using Microsoft Excel 2016), ii) the spearman correlation coefficient (MCC), iii) the Intraclass-correlation-coefficient (ICC(3,1)) and iv) Cronbach's alpha (CA) (using IBM SPSS Statistics 25). Concerning the MD and MCC, ten values arise from comparing the five trials for each sample. For further statistical comparisons the arithmetic means (M) and standard deviations (SD) were calculated.

To compare the trials to randomized matched curves, MTG-signals of the three different audioMTGAchilles were used to form five random groups. Only signals of the MTGAchilles audios were chosen, since the 40Hz-sine and the audioMTGtri show very different characterization compared to the MTGAchilles-signals and would skew the results significantly. The above listed parameters (1) to (4) for estimating the reliability were also calculated for the randomized groups.

Using IBM SPSS 25 the parameters (1) to (4) were tested concerning normal distribution using the Shapiro-Wilk test. To statistically compare the identical repetition trials to the randomized matched curves, the t-test for dependent samples was used in case of normal distribution (MCC, ICC) and the Wilcoxon-test for the not normally distributed parameters (MD, CA). Significance level was set at $\alpha = 0.05$.

Results

The curve shapes of the recorded repetition trials (*ex vivo*) are shown in Figure 2. In each diagram, five or ten repetitions are displayed illustrating good reproducibility. To illustrate the reproducibility of the oscillation characteristics of the original MTG-signals (*in vivo*) and the corresponding recorded audio sample from this investigation (*ex vivo*), Figure 3 shows examples of both signals and indicates that the frequency is reproduced precisely, but the amplitudes differ. The day-

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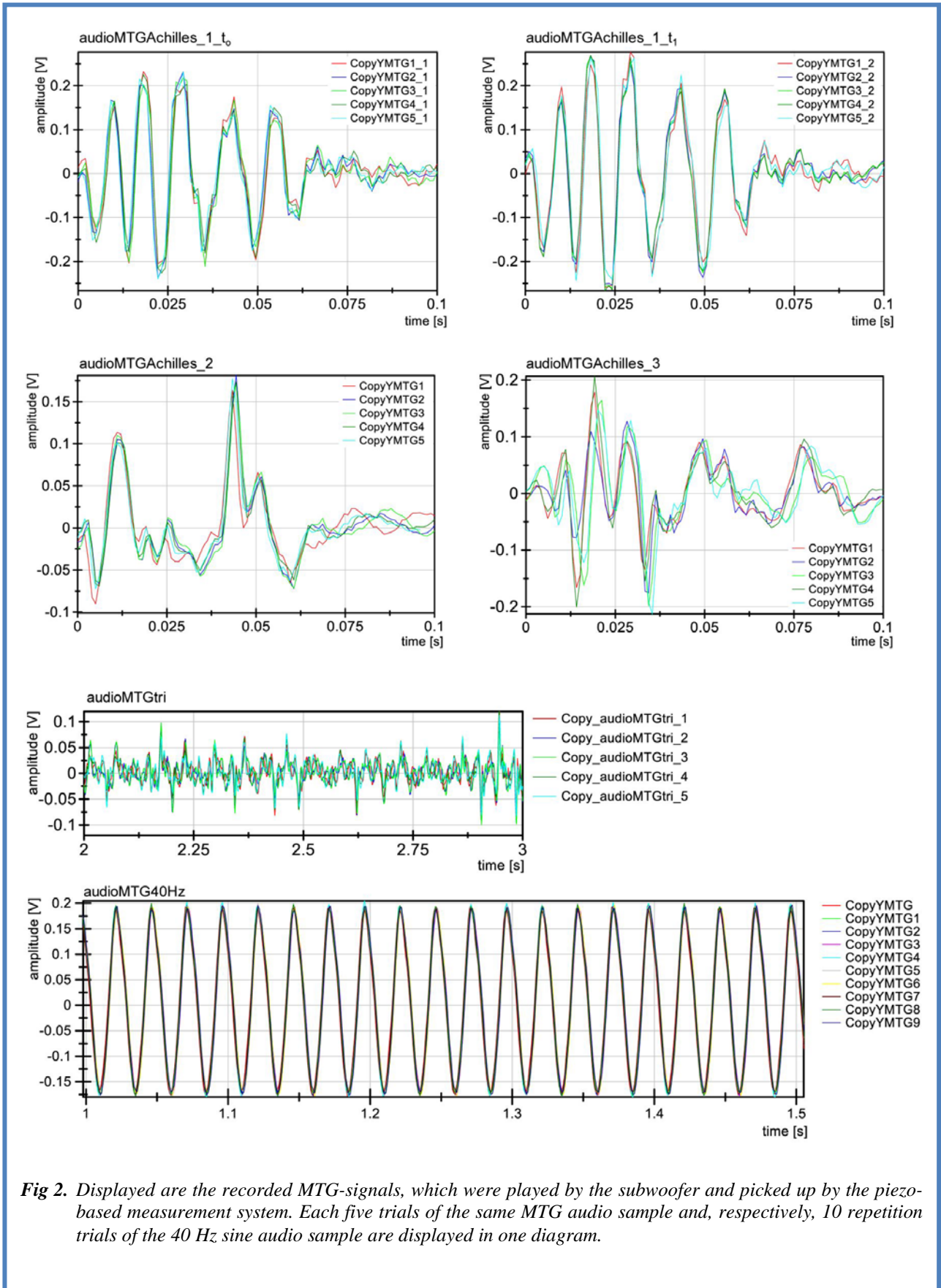


Fig 2. Displayed are the recorded MTG-signals, which were played by the subwoofer and picked up by the piezo-based measurement system. Each five trials of the same MTG audio sample and, respectively, 10 repetition trials of the 40 Hz sine audio sample are displayed in one diagram.

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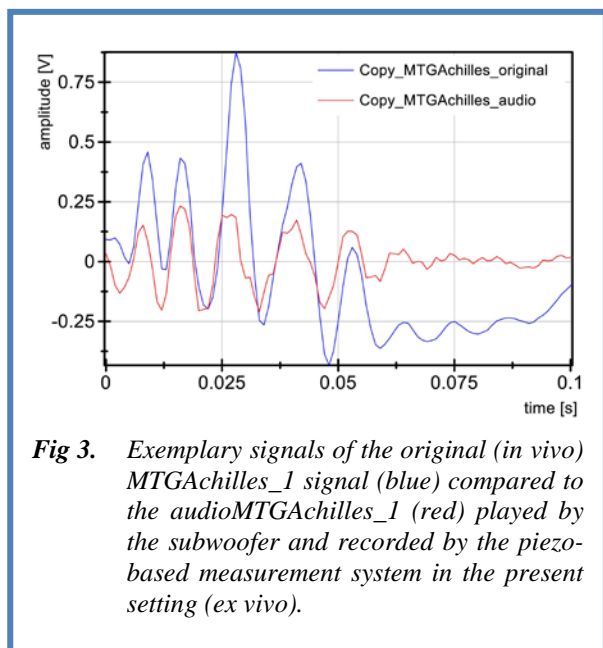


Fig 3. Exemplary signals of the original (in vivo) MTG_Achilles_1 signal (blue) compared to the audioMTG_Achilles_1 (red) played by the subwoofer and recorded by the piezo-based measurement system in the present setting (ex vivo).

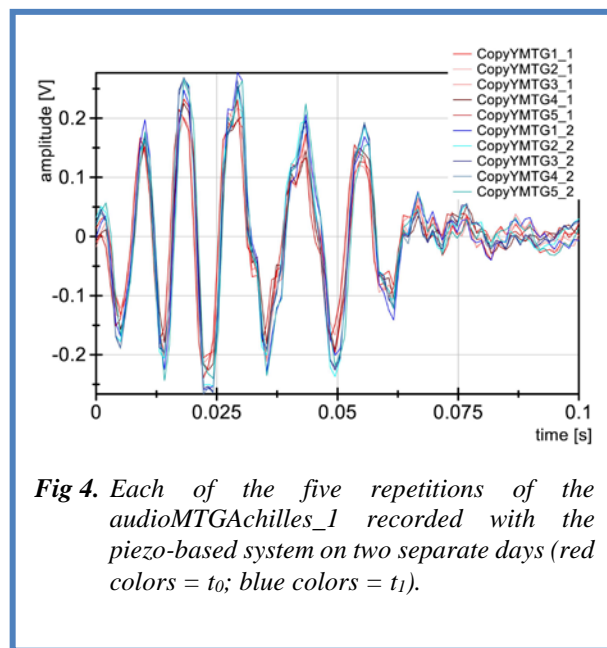


Fig 4. Each of the five repetitions of the audioMTG_Achilles_1 recorded with the piezo-based system on two separate days (red colors = t_0 ; blue colors = t_1).

to-day trials of the audioMTG_Achilles_1 are displayed in Figure 4. The 10 signals lie highly reproducible one above the other. To quantify this, parameters (1) to (4) are regarded.

Mean distances and correlation of repetition trials

The MD, MCC, ICCs and Cronbach's alpha between the identical repetition group and the random matched group are displayed for each recorded audioMTG-signal in Table 1. The comparisons of group averages ($M \pm SD$) are illustrated in Figure 5. The correlation coefficients (MCC, ICC, CA) show values from 0.67 to 1.0 for identical repetition trials, which indicate good to excellent reliability,³¹ whereas the randomized matched

groups show values from -0.01 to 0.25, which indicate no or poor reliability (Table 1). This is further supported by the group comparisons between identical and randomized matched groups. MCC and ICC show high significance with $t(4) = 9.104$ ($p = 0.001$, $r = 0.977$) and $t(4) = 9.317$ ($p = 0.001$, $r = 0.978$). The Cronbach's alpha shows lower, but still significant differences ($W = 2.023$, $p = 0.043$, $r = 0.905$).

These results indicate a significantly higher correlation for the identical repetition groups compared to the randomized matched ones.

The MD are significantly lower in the identical repetition group with averaged 0.03 ± 0.03 V compared to the randomized matched group with 0.19 ± 0.01 V

Table 1. The parameters averaged mean distances (MD), mean spearman correlation coefficient (MCC), Intraclass correlation coefficient (ICC(3,1)) and Cronbach's alpha (CA) calculated between each 5 identical repetition trials for each MTG-group and between randomized matched signals (MTG_rand) are displayed. Arithmetic means (M), standard deviations (SD) and coefficients of variation (CV) are given.

	Identical repetition trials					Random trials			
	MD	MCC	ICC	CA		MD	MCC	ICC	CA
audioMTG_Achilles_1_t0	0.03	0.73	0.72	0.93	MTG_rand_1	0.18	0.25	0.25	0.50
audioMTG_Achilles_1_t1	0.01	0.89	0.93	0.99	MTG_rand_2	0.19	0.17	0.21	0.44
audioMTG_Achilles_2	0.02	0.92	0.96	0.99	MTG_rand_3	0.20	0.14	0.14	0.33
audioMTG_Achilles_3	0.02	0.96	0.98	1.00	MTG_rand_4	0.17	0.20	0.23	0.46
audioMTGtri	0.08	0.67	0.76	0.94	MTG_rand_5	0.20	-0.01	0.04	0.11
audioMTG40Hz	0.02	0.99	0.99	1.00					
M	0.03	0.86	0.89	0.98	M	0.19	0.15	0.17	0.37
SD	0.03	0.13	0.12	0.03	SD	0.01	0.10	0.09	0.16
CV	0.84	0.15	0.13	0.03	CV	0.07	0.65	0.49	0.43

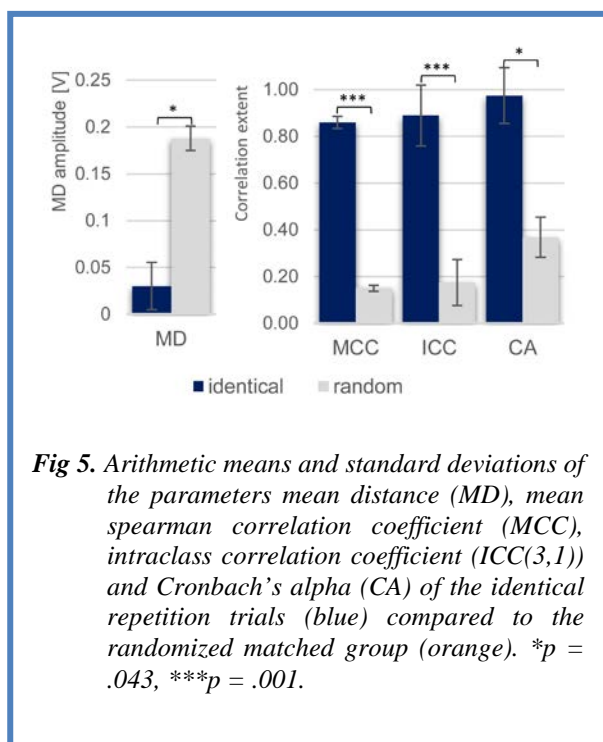


Fig 5. Arithmetic means and standard deviations of the parameters mean distance (MD), mean spearman correlation coefficient (MCC), intraclass correlation coefficient (ICC(3,1)) and Cronbach's alpha (CA) of the identical repetition trials (blue) compared to the randomized matched group (orange). * $p = .043$, *** $p = .001$.

($W = -2.023$, $p = 0.043$, $r = 0.905$), reflecting the smaller distances between the curves of the identical repetition trials compared to the randomized matched signals. For each comparison, a high effect size of $r > 0.90$ is obtained.

Discussion

The results of the present investigation examining the reliability of a piezo-based measurement system *ex vivo* show the significantly higher correlation values and significantly lower mean distances for the trials of the identical repetition group compared to the randomized matched ones. All parameter (1) to (4) display the similar curve behaviour during repetition trials of the same audio sample. This indicates a high reliability of the piezo-based measurement system *ex vivo*. The randomized matched signals behave inverse: The correlation parameters show, if at all, low correlation values and the MD are more than six times higher compared to the repetition curves of identical audio samples. This indicates a good distinction between different signals.

Reproducibility of MTG-signals

The comparison of the original audio signals (*in vivo*) and the recorded signals (*ex vivo*) (Figure 3) demonstrates a good agreement of wavelength indicating the high reproducibility of the frequency. The amplitude is lower in the recorded audio signal and partly shows signs of distortion. Reasons for this lie probably in the replay of the subwoofer. Because the undistorted original signals were detected *in vivo* by the same sensor type, the sensor can be excluded as origin for this phenomenon. It is likely produced by the speaker's coverage which is not as elastic as the speaker itself. Furthermore, especially in

low frequency areas below 30 Hz, the subwoofer might not be able to reproduce the sounds adequately. That was one reason to choose the *in vivo* MTG-signals of the Achilles tendon after impact as base for the audio samples, which show higher frequencies.³⁰ Since the mechanical oscillations of muscles and tendons during pure isometric muscle activity are located in frequency areas below 30 Hz,¹⁻³ the audio replay by the subwoofer might reflect those frequency areas not as good as the original MTG-signals. This limited frequency response is especially visible by comparing the original MTG-signal of the triceps brachii tendon and the re-recorded audio MTGtri-signal using the subwoofer (Figure 6). It is clearly visible that the signals do not match. This is led back to the low frequencies around 15 Hz of the MTGtri-signal. The repeated recordings of this MTGtri audio sample, however, indicate an excellent reliability $ICC(3,1) = 0.76$ ($p < 0.001$). It is concluded that the reproducibility of five repetition trials is very good, although the subwoofer shows a limited frequency response. It is assumed that with another subwoofer reproducing the low frequency ranges properly, the original and the recorded signals would be as similar as it was found for the MTG-signals of the Achilles tendon after impact. However, usually subwoofers are not required to play frequencies below 20 Hz, since they are not hearable for humans. Infrabass subwoofers would be able to reproduce such frequencies but are only used in the professional event areas and are very expensive. Therefore, an infrabass subwoofer was not applicable here. However, the aim of showing the reproducibility of repetition trials still is reached in the presented setting.

Reliability of repeated measurements using the piezo-based measurement system

The best reliability was found for the technical 40 Hz oscillations ($ICC(3,1) = 0.99$, $MCC = 0.99$), assuming that the piezo-based measurement system is suitable to record harmonic oscillations properly in amplitude and frequency from the mechanical pressure waves of a subwoofer. The oscillations produced by a muscle or tendon is rather comparable to inharmonic structure-borne sound. As was shown in the results, the reproducibility of a former biological inharmonic signal is also captured in a reliable way using the subwoofer. Therefore, it can be concluded that the piezo-based measurement system is a valuable tool to record mechanical pressure waves. This is not surprising regarding the common application of those sensors in music. If the piezoelectric sensor would not reproduce the mechanical pressure waves in frequency and amplitude appropriately, the sound would be distorted.

Advantages of piezoelectric sensors used for MTG/MMG.

From experiences in the Neuromechanics Lab, piezoelectric sensors (pickups) reflect the mechanical oscillations very precisely with an exceptional good

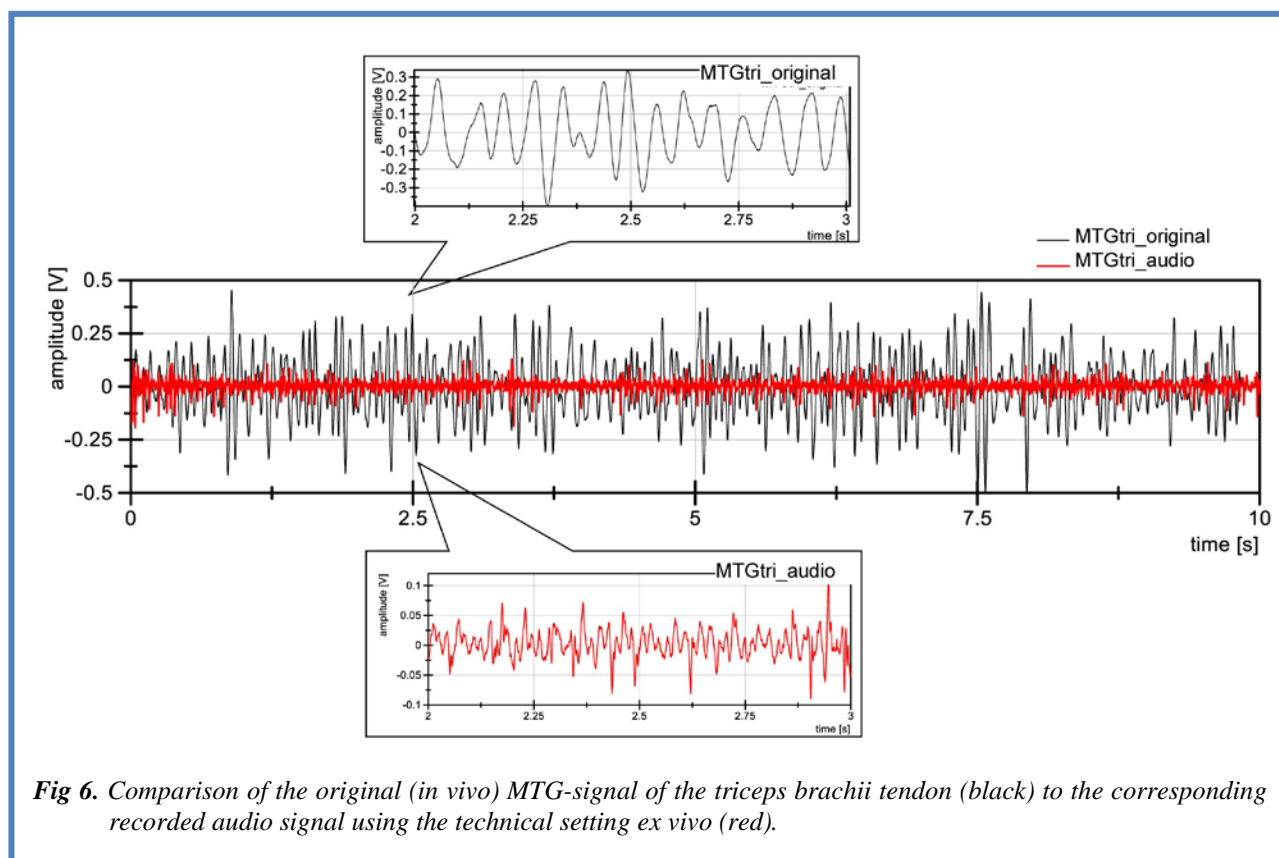


Fig 6. Comparison of the original (in vivo) MTG-signal of the triceps brachii tendon (black) to the corresponding recorded audio signal using the technical setting ex vivo (red).

signal to noise ratio (SNR). The raw data of the in vivo measurements are displayed in Figure 6, where no filtering or smoothing were performed. The signal shows clear, almost sinusoidal amplitudes with frequencies ~ 15 Hz. None of the acceleration sensors we tested could reproduce such clear signals directly from the muscle belly or the tendon.

However, not all piezoelectric sensors are suitable for MMG/MTG. We presented here the most appropriate ones from our experience. However, we already had a new batch of the Shadow SH 4001 sensor, which have changed in quality. Therefore, we switched to the Shadow SH-SV1, which proved to be suitable. There are other pickups, which turned out to be suitable regarding the SNR. However, they had a larger diameter and turned out to be not as practicable for fixing onto the skin above the muscle belly or tendon. Beside the choice of a suitable piezoelectric sensor, an essential factor is the used amplifier. As mentioned in the method the amplifier must be capable to amplify low frequency ranges for MMG/MTG. Since the Nobels preamp booster pre-1 turned out to be suitable and reveals extremely clear signals, they are used in our investigations.

Comparison of MTG signals ex vivo vs. in vivo

The piezo-based measurement system was already used in several MTG studies in vivo. It was shown that the MMG-/MTG-signal pairs of the triceps brachii muscle and its tendon develop high coherence between the muscle and tendon of one person and between two

interacting persons during isometric muscle action at 80% of the MVC.^{3,27} In contrast, randomized matched pairs did show significantly lower coherence.^{3,27} In case the system would produce random, distorted or noisy signals, a result like this would not appear. This also indicates that the used piezo-based measurement system is a valuable and valid tool to measure tendinous and muscular oscillations in vivo.

The comparison of the here presented reliability results in the technical setting to measures of a recently conducted study in patients with Achillodynia lead to further assumptions.³⁰ The MTG of the Achilles tendon was measured during an impact on the forefoot from plantar in direction of dorsiflexion during one leg stance. Patients with Achillodynia ($n = 10$) showed a significantly higher MCC and a significantly lower MD between the curves of five trials compared to healthy controls ($n = 10$).³⁰ In comparing those results with the here recorded audio trials, it is even more indicated that the oscillations of an affected Achilles tendon after impact in vivo behave similarly compared to the repetition trials ex vivo recording the same audio file (MCC: Achillodynia (in vivo): 0.85 ± 0.07 vs. audioMTGAchilles (ex vivo): 0.88 ± 0.13 ; MD: Achillodynia: 0.13 ± 0.03 vs. repeated audioMTGAchilles: 0.02 ± 0.03). In contrast, the healthy subjects in the Achilles tendon study showed a higher variability (lower MCC, higher MD). This behavior is rather comparable to the here presented randomized matched group (MCC: Achilles tendon (in vivo): $0.45 \pm$

0.39 vs. random audioMTGAchilles (ex vivo): 0.15 ± 0.10 ; MD: Achilles tendon: 0.23 ± 0.12 V vs. random audioMTGAchilles: 0.19 ± 0.01 V). This comparison indicates that immediately after an impact a healthy preloaded Achilles tendon oscillates in a more variable way, which tends to behave like randomized matched trials. Affected Achilles tendons (achillodynia) oscillate in a way, which rather matches the repeatedly recorded similar audio-signals of MTGAchilles (ex vivo), which show excellent reliability. It is assumed, therefore, that the higher variation in healthy controls is due to a necessary biological variability, which obviously plays an important role in healthy neuromuscular systems.

Because of their natural variability, biological systems will never produce identical wave patterns. Therefore, the validation of the reliability of such systems in vivo is limited. However, the high reproducibility of the tendinous oscillations in patients with achillodynia indicates that the piezo-based measurement system is not only suitable to capture the oscillations of audio samples in the here presented technical setting in a reproducible way but are also able to monitor oscillations of tendinous structures reliably.

Tendinous oscillations as possible insight into motor control

It is suggested that the mechanical oscillations captured superficially by the piezo-based measurement system reflect the motion of tendons. This is supported by the investigations using real-time ultrasound showing that the motion of the Achilles tendon and the adjacent subcutaneous tissue were similar.²² Therefore, it is conceivable that the mechanical pressure waves generated by those oscillations can be captured by the piezo sensors fixed on the skin. Tendons oscillate laterally and axially. The piezoelectric sensor is not able to display the axial motion due to the placement on the skin. However, using MTG, the mechanical pressure waves can be captured in the transversal plane.

A special feature regarding some tendons, e.g., the Achilles tendon or the tendon of the triceps brachii muscle, is that there is more than one muscle head, which inserts into the tendon. Thus, there is not only one single muscle working, but the three heads of the respective muscle. The cooperation of those three oscillating actuators is still not uncovered completely. However, as shown in terms of isometric muscle action, collaborating muscles and tendons can be synchronized by the neuromuscular system.^{3,27} It is assumed that the three muscle heads should also be able to develop coherent behavior, which is supposed to be controlled by supraspinal motor areas. Since all those muscle heads insert into one tendon, a superpositioning effect of the tendon is assumed for the Achilles or triceps brachii tendons. Measures of tendons, therefore, could reveal further insights into the quality of motor control processes. The Achilles tendon, e.g., is alternated tightened and released during walking. Due to the

impacts of floor during heel strike and the contraction of the triceps surae muscle during push off, the sinew is tightened. The behavior of the tendon during and after this impact is influenced by the active drives of the muscles but also by its passive mechanical properties. The tension and length of the tendon influence the resonance frequency like it is the case for a chord of a guitar. Thereby, the tendon functions as band pass. Certain frequencies are suppressed and the surrounding soft tissues will have a vibration damping effect. It is therefore assumed that the oscillations of tendons not simply reflect muscular vibrations. The behavior is highly influenced by the tension and the vibrations of their driving muscles. It is supposed that changes in the tendon's oscillatory pattern might reflect an impaired motor control.

Therefore, the investigation of those mechanical tendinous oscillations might provide a more functional insight into the properties of tendons. Hence, the non-invasive and easy applicable method of MTG could be a promising option to enlarge the knowledge of the behavior of those relevant body structures in healthy and diseased persons and to examine this promising tool for probable applications in diagnostics. The repetition trials showed that the used piezo-based measurement system is suitable to measure mechanical oscillations reproducibly. It is concluded that the MTG is a reliable and valid tool to measure tendinous oscillations. It seems reasonably transferable to muscular oscillations. The methods of MTG and MMG offer possibilities to get insights into the tendinous and motor output, which might reflect the functionality of the neuromuscular system and control. Therefore, the application of this innovative, non-invasive, low-cost, easy applicable method in further studies dealing with the neuromuscular system is suggested as one practicable approach. It might lead to additional knowledge of pathomechanisms and might help in diagnosing impairments of the neuromuscular system and of motor control.

Acronyms

audioMTGAchilles_1 – first audio file of in vivo recorded MTGAchilles
 audioMTGtri – audio file of in vivo recorded MTGtri
 CA – Cronbach's alpha
 ECG – electrocardiography
 EMG – electromyography
 Hz – Hertz
 ICC – intraclass correlation coefficients
 M – arithmetic mean
 MTG – mechanotendography
 MCC – mean Spearman correlation coefficient
 MD – mean distances
 MMG – mechanomyography
 MTG – mechanotendography
 MTGAchilles – MTG of Achilles tendon
 MTGtri – MTG of triceps brachii tendon
 SSI – Supersonic shear imaging

Authors contributions

LVS and FNB designed the study. LVS performed the measurements, data processing, analysis and drafted the manuscript. Both authors reviewed the manuscript critically.

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Conflict of Interest

The authors declare to have no conflicts of interests.

Ethical Publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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