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# REPEATABILITY OF MECHANICAL MUSCLE ACTIVITY MEASUREMENTS USING A MUSCLE CONTRACTION (MC) SENSOR: TIME-SERIES AND DISCRETE VARIABLE ANALYSIS OF THE VASTUS MEDIALIS

## PONOVLJIVOST MERITEV MEHANSKE AKTIVNOSTI MIŠIC Z UPORABO SENZORJA MIŠIČNE KONTRAKCIJE: ANALIZA ČASOVNIH VRST IN DISKRETNIH SPREMENLJIVK MIŠICE VASTUS MEDIALIS

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The primary objective of this study was to provide empirical evidence of the repeatability of the muscle contraction (MC) sensor signal and the associated measurement methodology based on a discrete covariate analysis. Despite the growing interest in this technology, the repeatability of MC sensor measurements across different environments and applications has not yet been systematically investigated, which is essential for establishing the reliability and practical applicability of these sensors. Therefore, this study presents a comprehensive repeatability analysis of MC sensor measurements obtained from the vastus medialis muscle of the thigh. This study provides strong evidence for the repeatability of muscle contraction (MC) sensor signals and the associated thigh muscle measurement methodology. Furthermore, the results highlight the potential of MC sensor technology for real-time investigation of mechanical muscle activity, offering a promising alternative to existing measurement techniques.

Keywords: MC sensor, muscle activity, repeatability, intraclass correlation, cross-correlation

Primarni cilj študije, predstavljene v članku, je bil zagotoviti empirične dokaze o ponovljivosti signala senzorja mišične kontrakcije (MC) ter pripadajoče merilne metodologije, ki temelji na analizi diskretnih kovariat. Kljub naraščajočemu zanimanju za to tehnologijo ponovljivost meritev z MC senzorji v različnih okoljih in aplikacijah doslej še ni bila sistematično raziskana, kar je ključno za vzpostavitev zanesljivosti in praktične uporabnosti teh senzorjev. Zato študija opisana v tem članku predstavlja celovito analizo ponovljivosti meritev MC senzorja, pridobljenih na mišici vastus medialis stegna. Rezultati zagotavljajo trdne dokaze o ponovljivosti signalov senzorja mišične kontrakcije (MC) ter pripadajoče merilne metodologije za stegenske mišice. Poleg tega avtorji v članku izpostavljajo potencial tehnologije MC senzorjev za sprotno (realno-časovno) preučevanje mehanske mišične aktivnosti, ki predstavlja obetavno alternativo obstoječim merilnim tehnikam.

Ključne besede MC senzor, mišična aktivnost, ponovljivost, medrazredna korelacija, navzkrižna korelacija

## 1 INTRODUCTION

Muscles are essential for human movement, force generation and metabolism. However, measuring their mechanical behavior under dynamic loading conditions is difficult using conventional methods such as electromyography (EMG)[1] or surface electromyography (sEMG),[2] which only record their electrical activity and thus indirectly reflect the mechanical behavior of the muscles, or mechanomyography (MMG),[3,4] which records the vibrations generated by muscle activation, such as phonomyography, sound myography and vibromyography.[5] The MC sensor, introduced in 2011 by TMG-BMC Ltd., Ljubljana, Slovenia, is a novel device that directly measures mechanical variables such as muscle tension by recording the force on the subject's skin over the muscle[6–11] to overcome the limitations of EMG and MMG, which are susceptible to skin electrode placement and impedance, movement artifacts, muscle fatigue and external factors,[12–16] offering direct measurement of muscle displacement rather than electrical or vibrational activity.[13]

It consists of a sensor tip that compresses the skin and intermediate layer above the muscle to be measured, a force gauge and a support piece that is attached to the subject's skin. This technique is based on the selective tensiomyographic measurement of the displacement of the muscle belly. When a skeletal muscle contracts, the tension of that muscle changes and the sensor records the vector sum of the force in the direction of the sensor, which is proportional to the muscle tension.[10] The MC sensor can also indirectly measure biomechanical parameters such as intra-abdominal pressure.[17]

However, the repeatability of MC sensor measurements in different environments and applications has not yet been systematically investigated, which is crucial for

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establishing their utility and reliability. This study aims to fill this gap by performing a comprehensive repeatability analysis of MC sensor measurements on the vastus medialis muscle under controlled dynamic conditions. Two complementary analysis approaches were planned: a time series analysis of the whole signal, which examines the temporal variations in sensor readings from selected muscles, and a discrete analysis, which is based on the standard parameters used in twitch contraction studies.[18–20]

We hypothesized that by performing a discrete analysis of covariates following an external muscle stimulus, we would prove that the use of the MC sensor and its signal is a reliable method for measuring muscle tension and time-dependent activation under controlled dynamic conditions.

## 2 EXPERIMENTAL PART

Seventeen test subjects aged 19–40 years took part in this study. The MC sensor was placed on the subjectively dominant leg over the most prominent part of the vastus medialis head of the quadriceps muscle and attached with an adhesive pad. The corresponding MC logger (MC-System, TMG-BMC, Ljubljana, Slovenia) was used to record changes in muscle tension. Two self-adhesive electrodes (PALS, Axelgaard, USA) were positioned 4 cm distal (cathode) and 4 cm proximal (anode) to the thickest part of the vastus medialis muscle belly, as identified during voluntary isometric contraction. The tip of the MC sensor (8 mm) was placed centrally between the electrodes. After each placement of the electrodes, subjects were asked to wait 2 minutes to allow the skin to adapt to the initial pressure.

A single-twitch electrical stimulus of 100 mA direct current (square pulse, duration of 1 ms) was delivered to the vastus medialis muscle with a synchronized TMG-S2 stimulator (TMG-BMC, Ljubljana, Slovenia) at 90° knee flexion. After each stimulus, muscle activity was recorded, followed by another stimulus with a time delay of 10 s. For each measurement, 10 consecutive stimuli were delivered as shown in **Figure 1**. This was the basis for immediate repeatability. Mean repeatability was performed 30 min later using the same protocol without any adjustment of the sensors or stimulator. After these measurements, the sensor and electrodes were removed and reapplied to the marked site after 240 min. The same measurement protocol was used, which formed the basis for the delayed repeatability.

The MC sensor was used to continuously record muscle activity in the vastus medialis head during a measurement of 10 stimuli. The sensor was configured to record the fluctuations in muscle activity during the measurements, with the data sampled at 1 kHz. After triggering each electrical stimulus, the corresponding segment of the recorded signal was extracted and determined as the onset of the signal for analysis. The duration of this extracted signal segment was set to 260 ms and included both the peak amplitude of the muscle contraction and the onset of the relaxation phase. A low-pass Butterworth filter of order 8 with a cut-off frequency of 100 Hz was used to reduce the influence of high-frequency noise on the signal.

### *2.1 Statistical analysis*

Cross-correlation coefficients measure the similarity or relationship between two time series as a function of the shift or lag of one relative to the other. OriginLab (Originlab Corporation, Northampton MA, USA) and the Python programming language (Python Software Foundation, Wilmington, DE, USA) were used to calculate cross correlation. The parameters tRmax (the corresponding time shift value for the maximum correlation between the two signals) and R95 % (correlation within

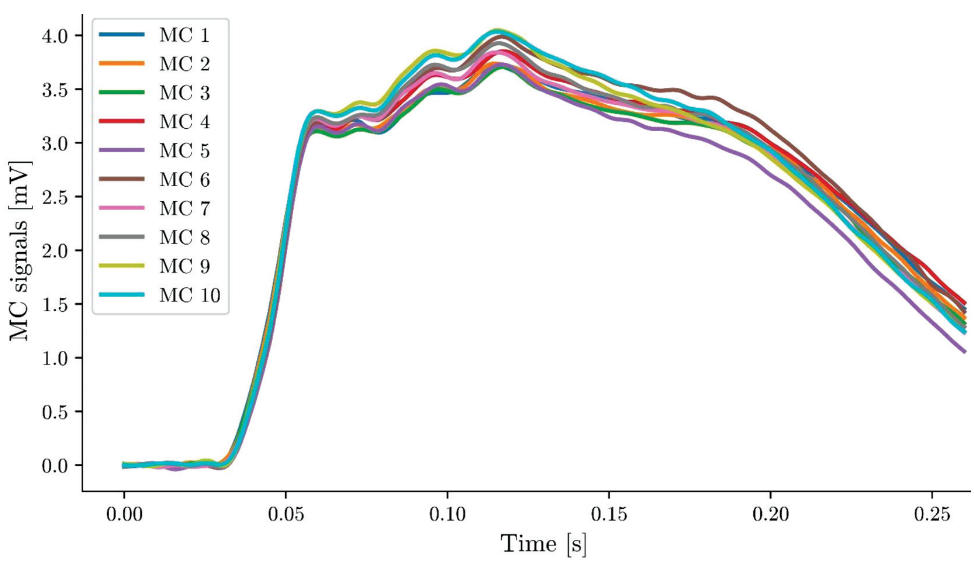


**Figure 1:** MC signals of 10 consecutive stimuli to vastus medialis

the 95 % confidence band) were calculated for each pair of measurements using the algorithm described in reference.[21]

The intraclass correlation coefficient (ICC k1) was computed with Python using the Pingouin statistical package's intraclass_corr function[22] for the following parameters: the delay time (Td), time to reach maximum amplitude (Tc), and the magnitude of the amplitude (Dm), shown in **Figure 2**. The algorithm for calculating Td (delay time from 0–10 % of maximum amplitude during twitch contraction), Tc (time to reach 10–90 % of maximum amplitude), Dm (magnitude of amplitude at 100 % of twitch contraction) – was the same as for the TMG signal analysis.[9,10] It should be noted that the choice of discrete parameters is inherently susceptible to various forms of distortion. In addition, the repeatability of the measurements may depend on the specific algorithms used to extract the variables. For this reason, the choice of the two analytical approaches seems reasonable.

The cross-correlation and ICC-K1 analyses were first applied in the immediate repeatability framework and then extended to the intermediate and delayed repeatability by comparing each measurement with the corresponding measurements in the immediate repeatability experiment.

## 3 RESULTS

The results show a high reliability of the MC sensor signals and the parameters – delay time (Td), time to reach 10–90 % of maximum amplitude (Tc), and amplitude magnitude at 100 % of twofold contraction (Dm) – across different repetition methods (immediate repeatability, intermediate repeatability, delayed repeatability). In addition, the cross-correlation coefficients (R95) also show a strong similarity between the continuous sensor signal sets and a low time delay at the maximum correlation (tRmax). The high ICC values for Dm, Td and Tc indicate consistent measurements and good repeatability, with values close to 1 indicating excellent agreement. Despite a slight decrease in the values for immediate, intermediate and delayed repeatability, interclass correlation (ICC) values remain high, indicating reliable measurements even after repeated procedures. The numerical data are shown in **Table 1**. The cross-correlation analysis consists of the mean cross-correlation (R95) and the mean time lag at maximum correlation (tRmax), while

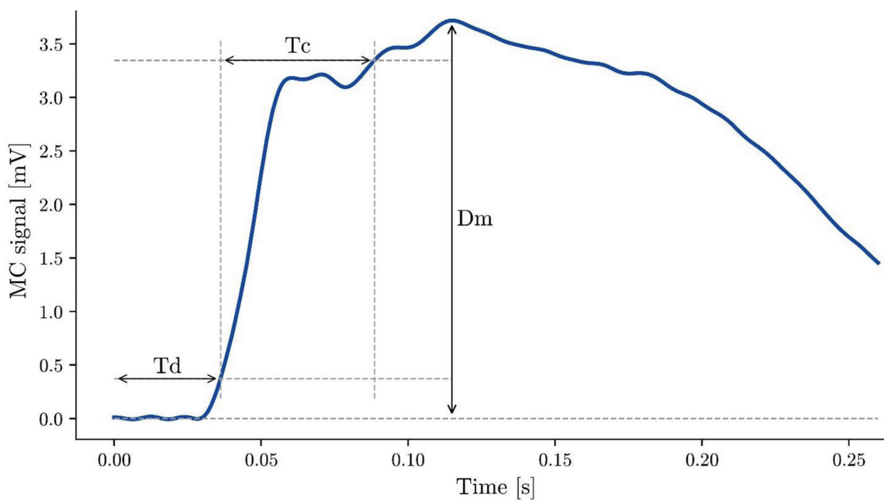


**Figure 2:** Parameters of intraclass correlation – delay time (Td), time to reach maximum amplitude (Tc), and magnitude of amplitude at 100 % of twitch contraction (Dm)

**Table 1:** Cross-correlation analysis and intraclass correlation analysis (ICC)

| Cross-correlation analysis | Mean cross-correlation (R95) | Mean time delay at maximum correlation (tRmax) | |
|---|---|---|---|
| Immediate repeatability | 0.995 | 0.39 ms | |
| Intermediate repeatability | 0.992 | 0.79 ms | |
| Delayed repeatability | 0.975 | 0.78 ms | |
| Intraclass correlation (ICC) analysis | ICC for Dm | ICC for Td | ICC for Tc |
| Immediate repeatability | 0.999 ($p < 0.0001$) 95% CI [0.99, 1] | 0.995 ($p < 0.0001$) 95% CI [0.99, 1] | 0.973 ($p < 0.0001$) 95% CI [0.93, 0.99] |
| Intermediate repeatability | 0.998 ($p < 0.0001$) 95% CI [0.99, 1] | 0.994 ($p < 0.0001$) 95% CI [0.98, 1] | 0.953 ($p < 0.0001$) 95% CI [0.87, 0.98] |
| Delayed repeatability | 0.994 ($p < 0.0001$) 95% CI [0.98, 1] | 0.969 ($p < 0.0001$) 95% CI [0.92, 0.99] | 0.963 ($p < 0.0001$) 95% CI [0.89, 0.99] |

the intraclass correlation analysis consists of the intraclass correlation coefficients for the lag time (ICC for Dm) from 0–10% of the maximum amplitude during the twitch contraction, the time to reach 10–90 % of the maximum amplitude (ICC for Tc) and the magnitude of the amplitude at 100 % of twitch contraction (ICC for Dm).

## 4 DISCUSSION

The main objective of this study was to provide empirical evidence for the repeatability of the MC sensor signal and the measurement methodology based on discrete analysis of covariates. However, the repeatability of MC sensor measurements in different environments and applications has not been systematically investigated, which is crucial for establishing their utility and reliability. Therefore, we conducted a comprehensive repeatability analysis of MC sensor measurements on the vastus medialis muscle of the thigh.

This approach involved electrical twitch stimulation, which triggered a dynamic contraction of the vastus medialis muscle in our experimental setup and caused a slight extension of the knee. Our primary research objective was to evaluate the repeatability of the amplitude of the MC sensor signal, which had previously been shown to correlate with the force of muscle contraction or changes in muscle tension.[10] In addition, we chose three different time frames to ensure the coherence of the internal and external environments. The intervals chosen for the comparative analysis of muscle contraction – 10 s, 30 and 240 min – were justified by their similarity to previous experimental designs investigating the influence of muscle activity on variables such as twitch potentiation, post-activation potentiation and muscle fatigue, as well as to studies investigating single muscle activity in the context of repetitive motor tasks.[23,24] The results of the study show the repeatability of the MC sensor measurements. The cross-correlation coefficients as well as tRmax and R95 % calculations demonstrated high similarity and correlation of the MC signals across the entire time interval (260 ms), indicating that the MC sensor consistently captures the same signal patterns with minimal time delay, even after longer intervals.

The ICC values for amplitude magnitude, delay time, and time to reach maximum amplitude demonstrate excellent repeatability across all intervals. These values suggest that the MC sensor provides highly consistent measurements of muscle tension. Similar studies have already demonstrated absolute and inter-rater reproducibility using similar protocols in tensiomyography.[20,25–31] Compared to the systematic review of nine studies by Martín-Rodríguez et. al., our results show even better values of the interclass coefficient for Td and Tc values.[13] Our ICC values were higher than those reported by several similar EMG studies, indicating that they are less susceptible to artifacts, noise, and electrode placement.[32–34]

While sensor repositioning and electrode placement might introduce variability, the high ICC and cross-correlation values indicate that the MC sensor is largely unaffected by these variables, underscoring its robustness. The results suggest that the MC sensor can provide reliable and repeatable measurements of mechanical muscle activity in a selected muscle, offering potential advantages over conventional methods such as EMG/M-wave and MMG.

## 5 CONCLUSIONS

This study provides evidence for the repeatability of MC sensor signals and thigh muscle measurement methodology. Furthermore, the results underline the potential of MC sensor technology for investigating mechanical muscle activity in real time compared to other existing technologies.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Institutional Review Board (or Ethics Committee) of the National Medical Ethics Committee of the Republic of Slovenia (Komisija Republike Slovenije za medicinsko etiko (KME)) (0120-110/2022/2, approved on 19.04.2022), for studies involving humans.

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