Wearable Multi-Frequency and Multi-Segment Body Impedance Spectroscopy (WM_BIS) in Sports and Rehabilitation Medicine

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Background

Body Impedance Spectroscopy (BIS)
may assess the composition of body districts
noninvasively and quickly.

For this reason, BIS can provide
important physiological or clinical information
for sport-medicine studies
or rehabilitation protocols.

Background

However, available instruments
do not **simultaneously** satisfy the demanding needs
that exercise/rehabilitation tests often requires, i.e.,

* recording BIS unobtrusively
* over a broad frequency range
* for long periods
* in different segments at the same time
* with high measurements rate.

Aim

Therefore our aim is to present a new prototype:

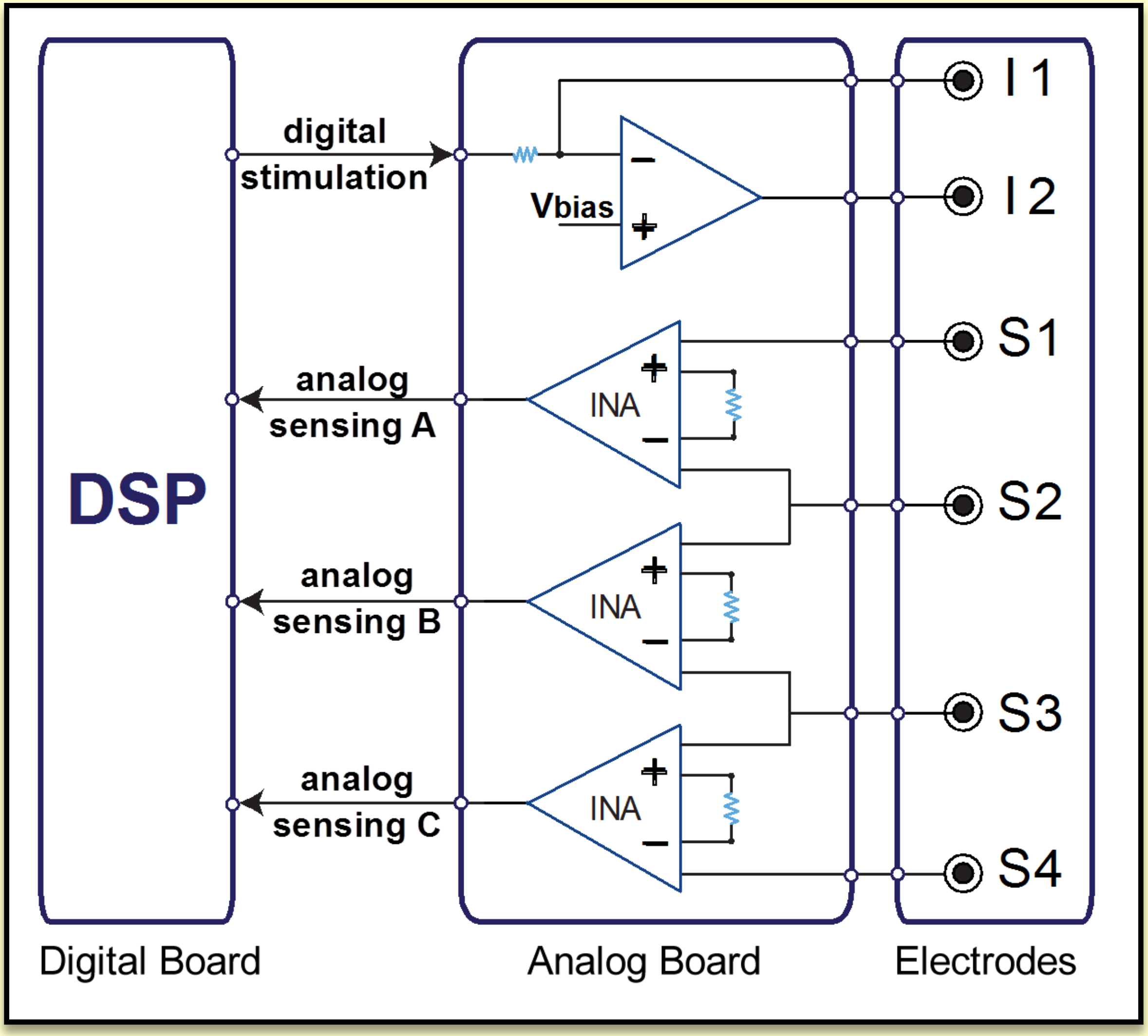
1) designed for monitoring
multi-segment, multi-frequency BIS,
unobtrusively over long periods

2) that guarantees wearability
with its low weight, small size
and low power consumption.

Our prototype, WM_BIS, should meet the needs required
for rehabilitation or sport-medicine studies:

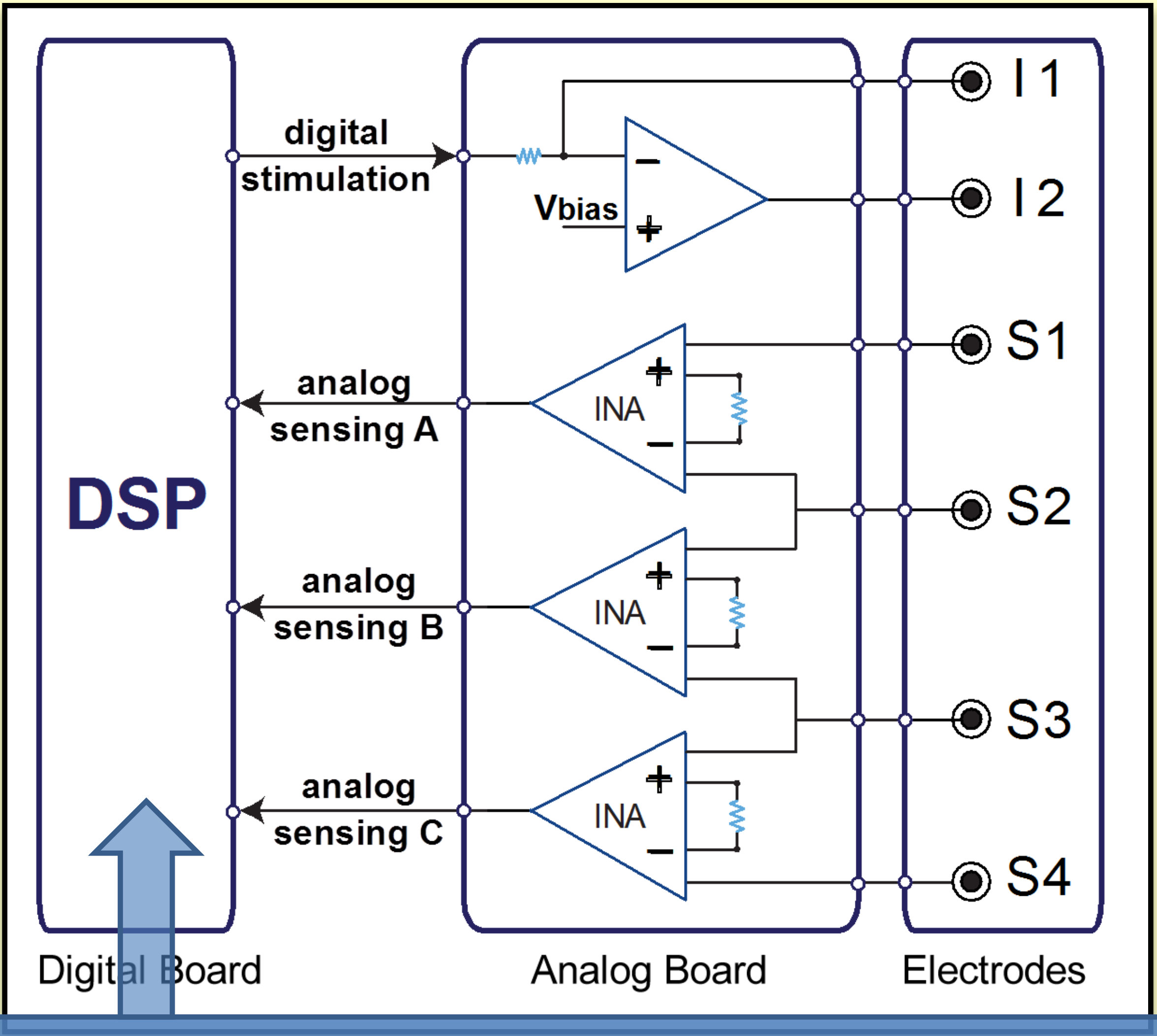
for this reason, its performance is illustrated
with an application in the field of sports and rehabilitation medicine.

Design of the wearable BIS system



The system consists in two boards: a digital board with a DSP (Texas Instrument C2000 "Piccolo family", 80 MHz clock) and a custom analog board

Design of the wearable BIS system



The DSP generates the stimulus waveforms, samples and digitalizes the voltage across three body segments with its 12-bit Analog to Digital Converter (ADC) and computes magnitude and phase of impedance, *Z(f)*.

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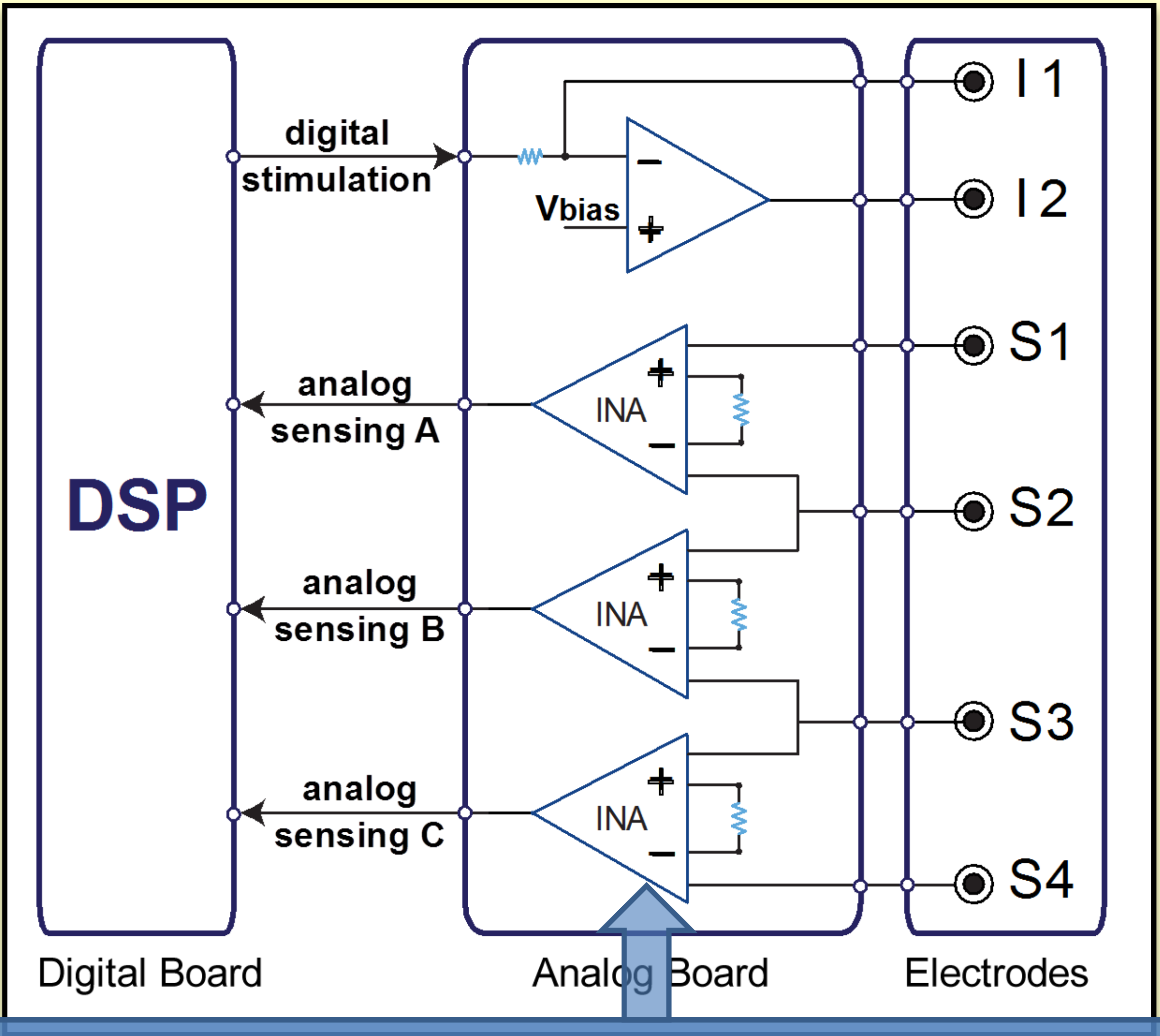

The analog board interfaces the DSP with the electrodes. A transimpedance amplifier is connected to two injecting electrodes; three instrumentation amplifiers (INAs) read the voltages across three body segments by means of four sensing electrodes.

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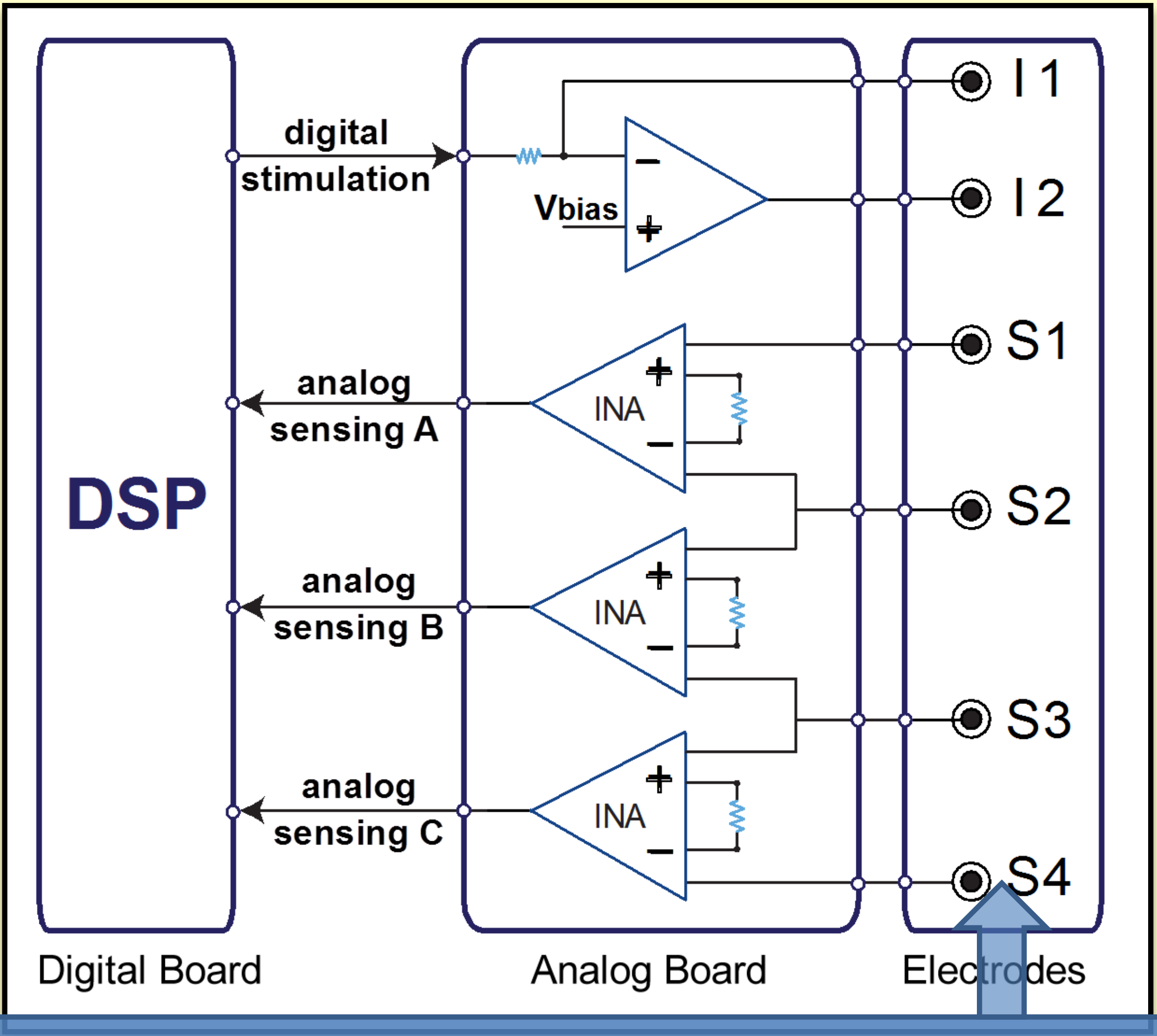

By using separate injection and sensing electrodes,
measures are independent from the electrode impedance
(this allow using small disk electrodes, avoiding band electrodes of larger area)

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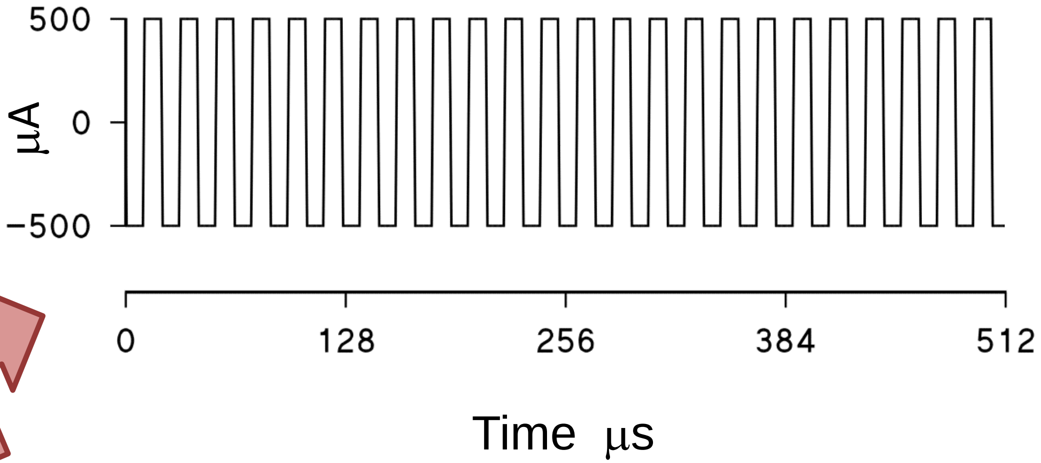

Example of waveform with period =1/48 kHz

The stimulation waveform is not a sinusoid (as in commercial BIS devices) but a square wave.

DSPs easily generate square waves and this waveform allows minimizing power consumption, size and cost

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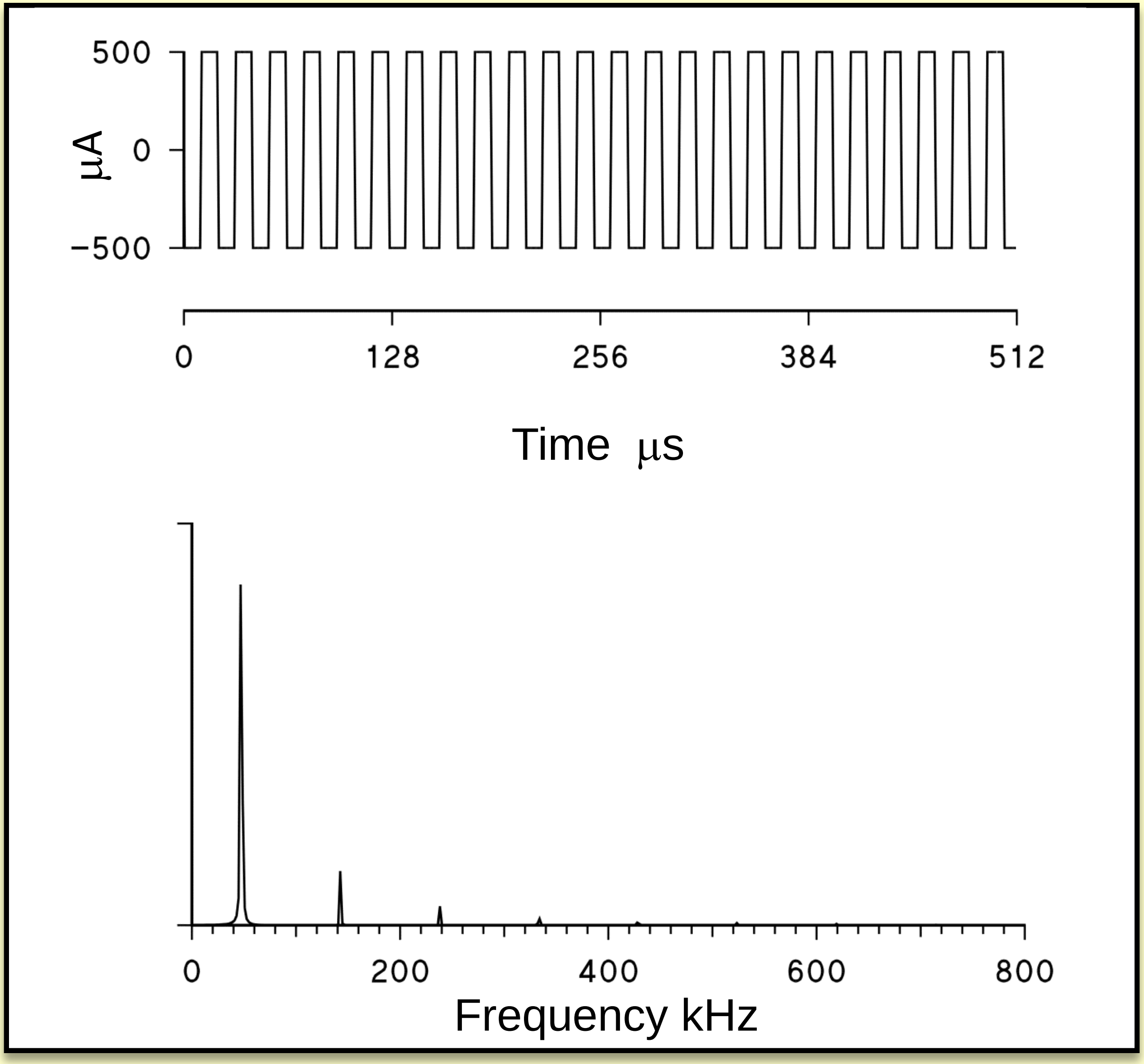
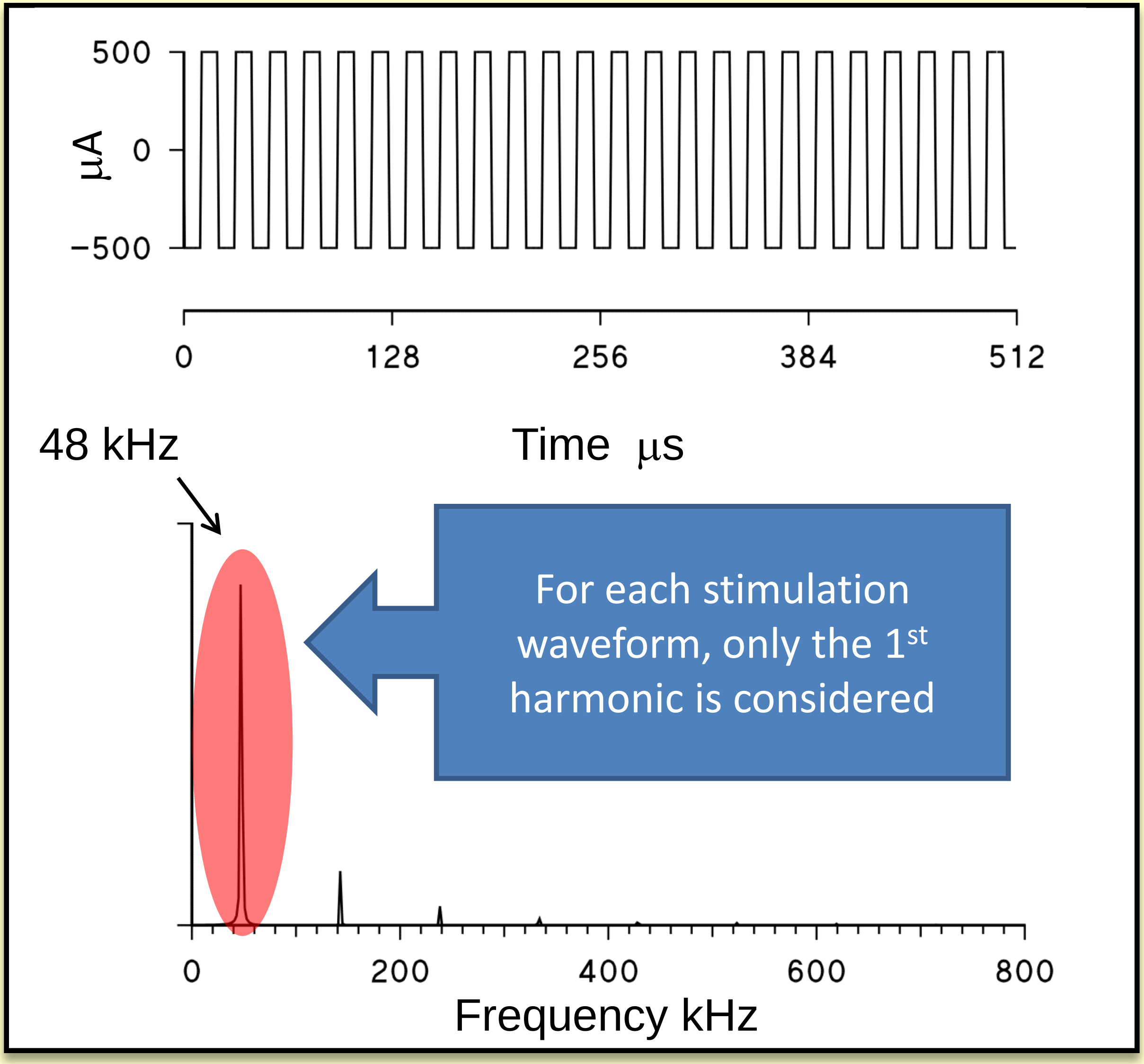


The DSP extracts magnitude and phase of *Z(f)* by FFT of the sensed voltage

Design of the wearable BIS system



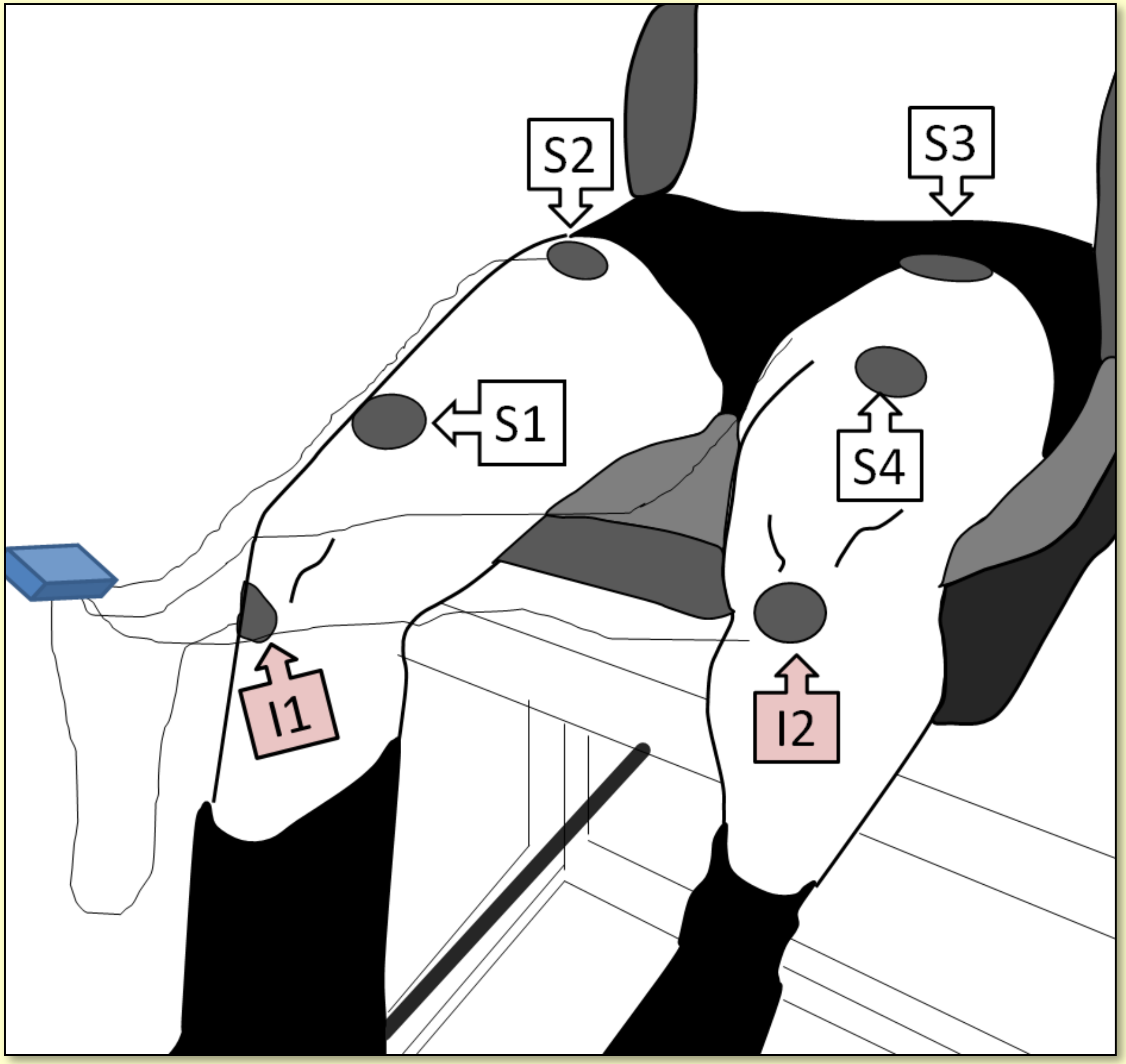
For each stimulation waveform, only the 1st harmonic is considered

The DSP extracts magnitude and phase of *Z(f)* by FFT of the sensed voltage

Realized Prototype

size = 8.5 × 5.5 × 2 cm^3;
weight <100 g;
total power consumption <100 mW

Experimental Set-Up



We instrumented a volunteer with an injecting electrode on each knee (I1 and I2), sensing electrodes on distal and proximal endings of the rector femoris muscle belly of the two thighs. Monitored segments were right (S1-S2) and left (S3-S4) thighs and pelvis (S2-S3).

Experimental Set-Up

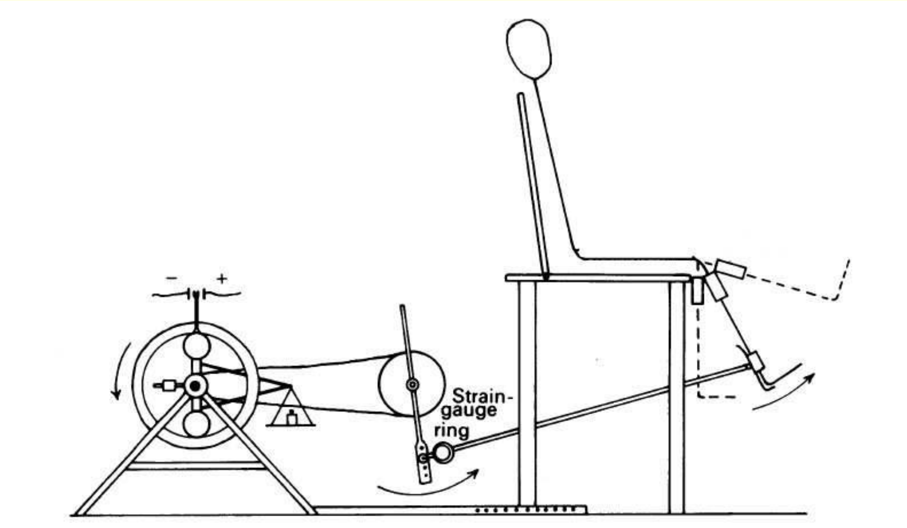
Baseline
7 minutes

Exercise
20 minutes

Recovery
20 minutes

Standing
7 minutes

Volunteer sitting on a one-legged knee-extensor ergometer



Experimental Set-Up

Baseline
7 minutes

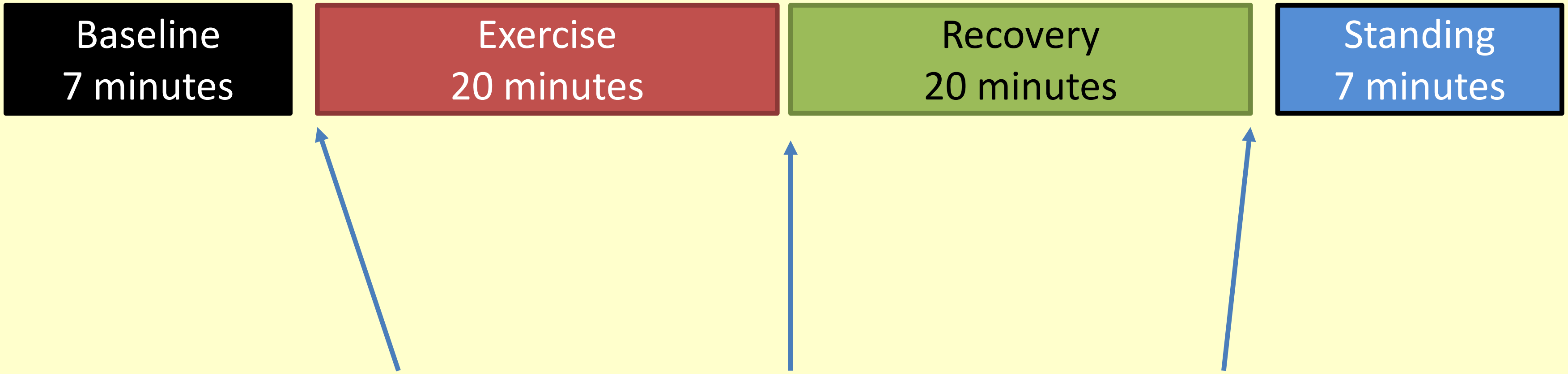
Exercise
20 minutes

Recovery
20 minutes

Standing
7 minutes

EXERCISE= repeated kicking extending the knee of the right (dominant) leg, at 60 extensions/minute.
The ergometer load was set at 25 watts with the exclusion of the initial warm-up (10 watts)
and of the last 2 minutes (50 watts).

Experimental Set-Up



Baseline
7 minutes

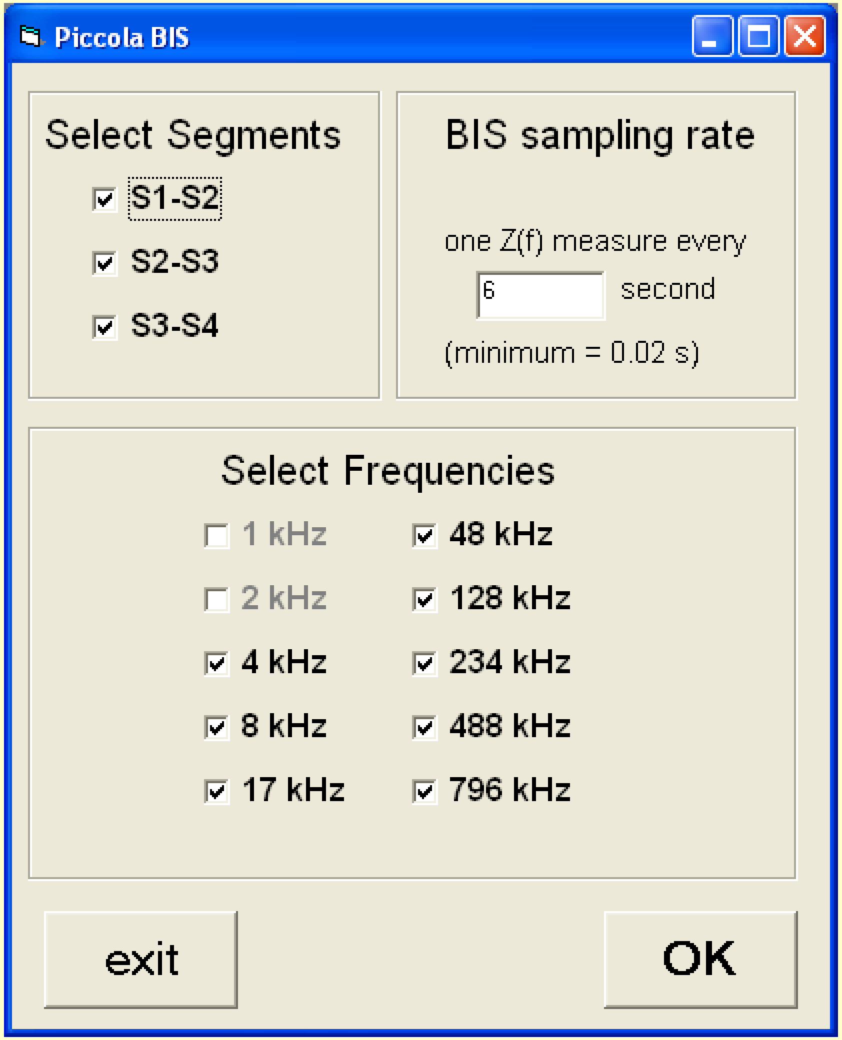
Exercise
20 minutes

Recovery
20 minutes

Standing
7 minutes

Subsequent conditions were spaced by few minutes to exclude transition phases

Experimental Set-Up



Select Segments

☑ S1-S2
☑ S2-S3
☑ S3-S4

BIS sampling rate

one Z(f) measure every 6 second

(minimum = 0.02 s)

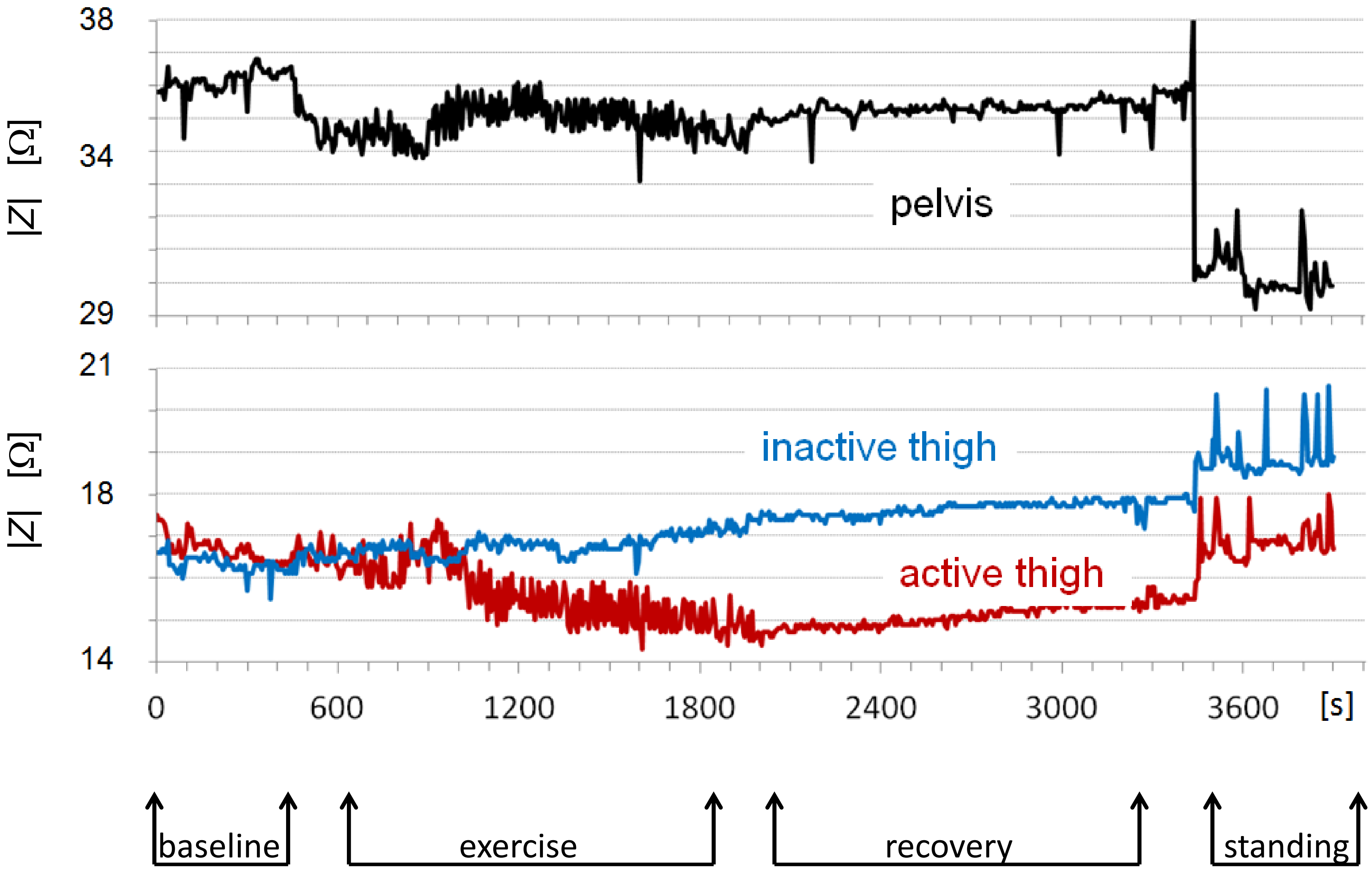
Select Frequencies

☐ 1 kHz
☐ 2 kHz
☑ 4 kHz
☑ 8 kHz
☑ 17 kHz
☑ 48 kHz
☑ 128 kHz
☑ 234 kHz
☑ 488 kHz
☑ 796 kHz

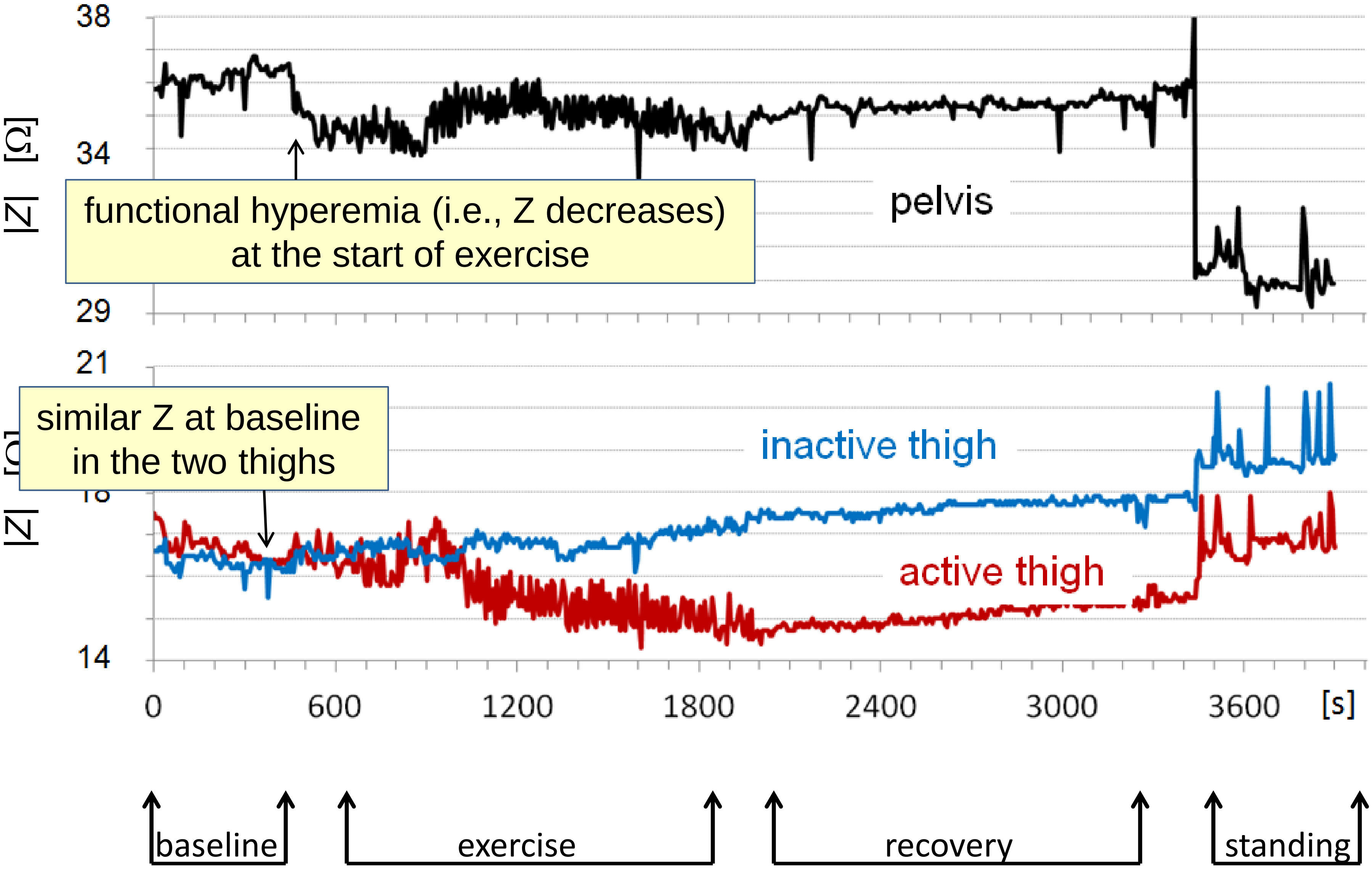
The device was set
for providing Z(f) of the 3 body segments
simultaneously every 6 s
(maximum sampling rate = 50 Hz)

at 8 of a maximum of 10 frequencies
equispaced in a log-scale
between 1 kHz and 796 kHz

Results: $|Z(f)|$ at f=48 kHz



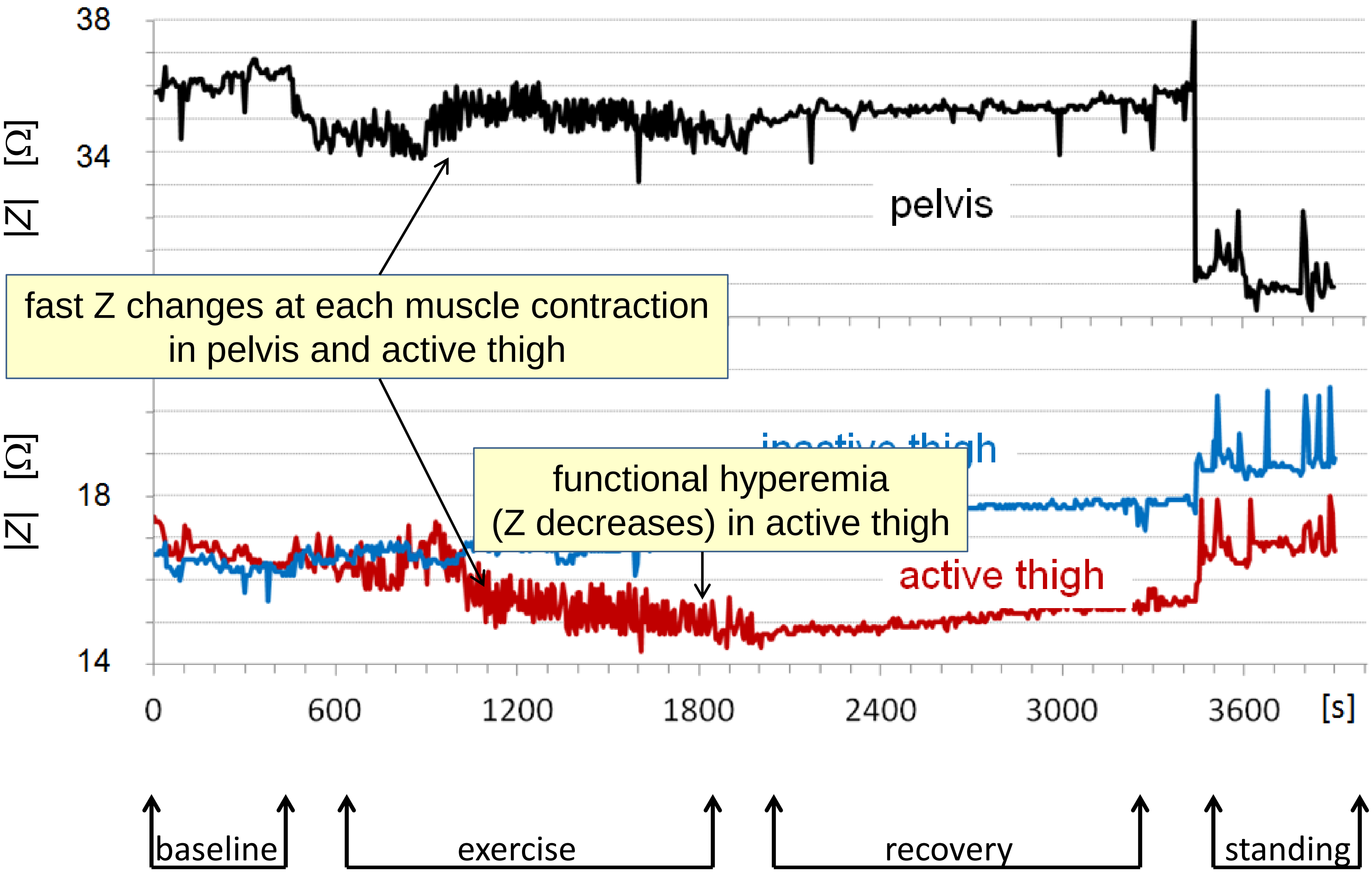
Results: |Z(*f*)| at *f*=48 kHz



functional hyperemia (i.e., Z decreases) at the start of exercise

similar Z at baseline in the two thighs

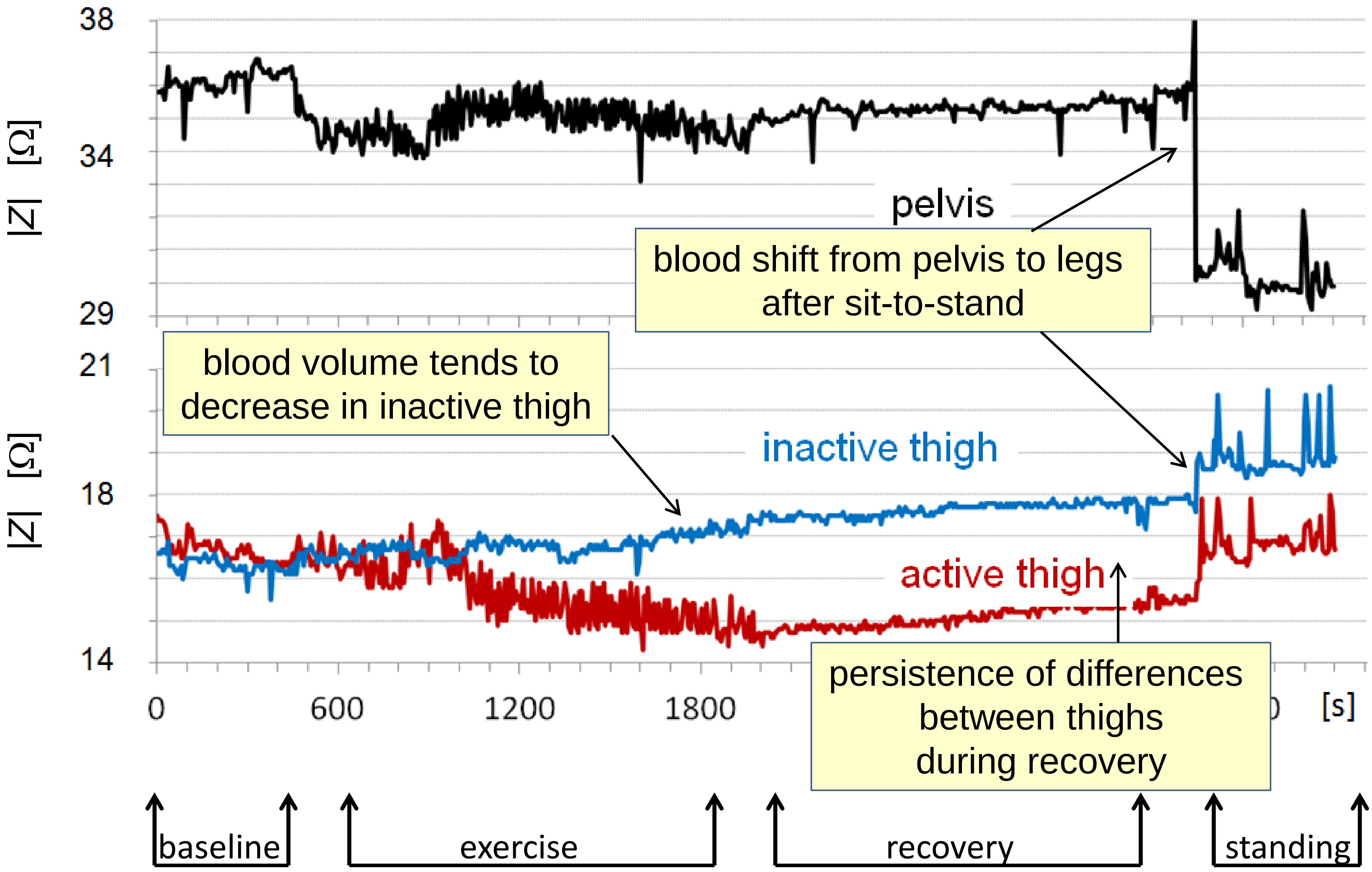
Results: $|Z(f)|$ at f=48 kHz



fast Z changes at each muscle contraction in pelvis and active thigh

functional hyperemia (Z decreases) in active thigh

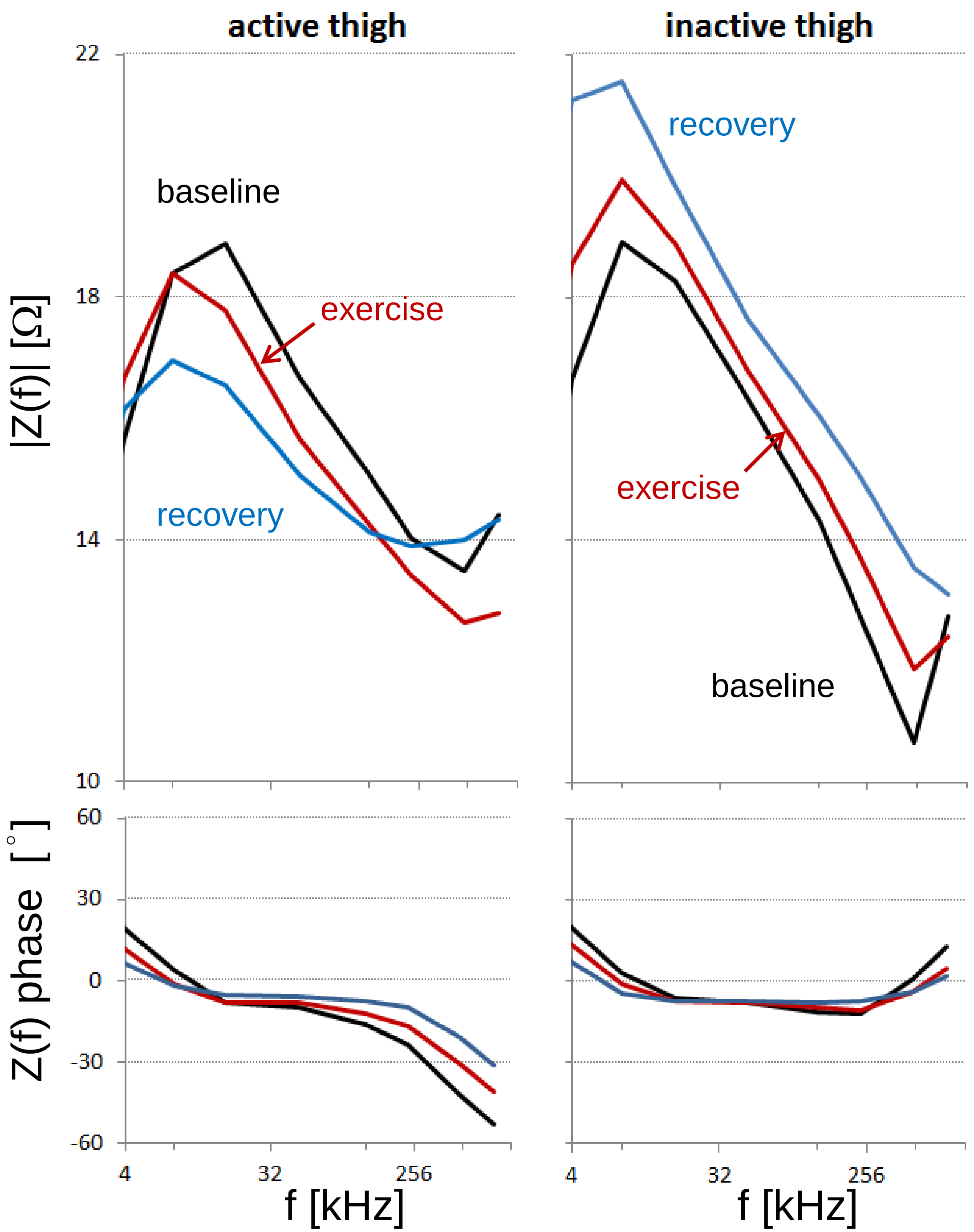
Results: |Z(*f*)| at *f*=48 kHz



blood shift from pelvis to legs after sit-to-stand

blood volume tends to decrease in inactive thigh

persistence of differences between thighs during recovery



Z(f) **in the thighs during the knee-extensor test**

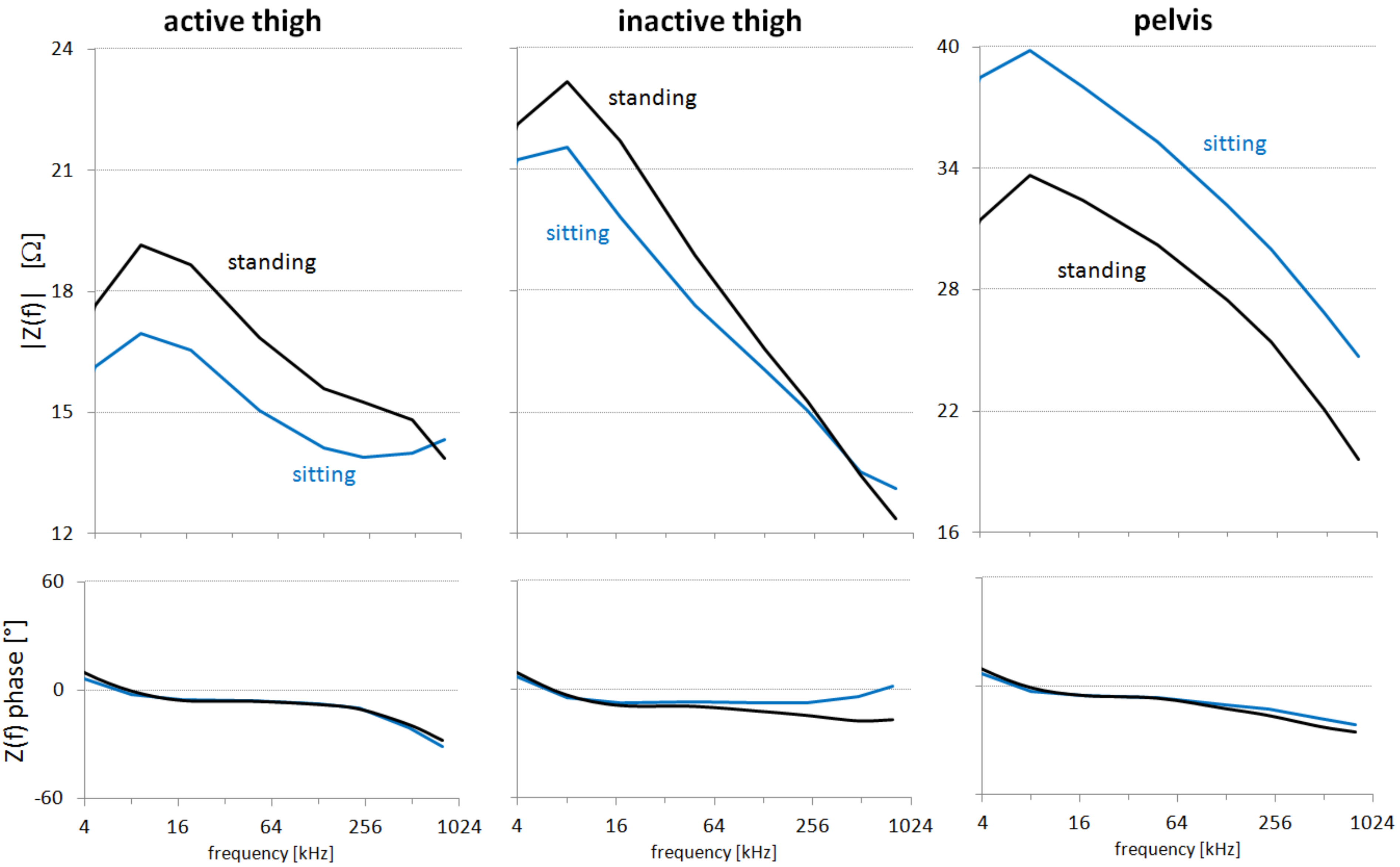
We found opposite trends from **baseline** to **exercise** and to **recovery**:

|*Z(f)*| decreased
in the active thigh

|*Z(f)*| increased
in the inactive thigh.

Changes are more pronounced
between 16-64 kHz
in the active thigh,

between 4-16 kHz
in the inactive thigh.



Z(f) from sit to stand during recovery.

|Z(f)| of thighs <u>increased</u>, mainly at the lower frequencies.

|Z(f)| of pelvis <u>decreased</u>, uniformly over the whole frequency band

Discussion

The exercise test illustrated the amount of information
that our wearable BIS device may provide.

Actually, our system was able to **quantify BIS dynamics**
over very different time scales,
from the fast changes due to each muscle contraction
up to long-term trends during recovery.

By monitoring different body segments simultaneously,
it was able to detect shifts of blood volumes
among contiguous districts.

In particular, it showed that the effect of the knee-extensor exercise
regards different frequencies on the active and inactive thigh,
suggesting that the blood shift between legs
changes the ratio between intra-cellular and extra-cellular liquids.
This finding would not be observed with traditional mono-frequency systems.

Conclusions

Our prototype has the lightness, wearability and unobstrusiviness
required by “real field” studies of sports and rehabilitation medicine.

Specific technical solutions
(DSP, square wave stimulations, small disk electrodes)
allow monitoring more segments simultaneously
and continuously for long periods.

This makes it possible
describing different body segments at the same time,
with frequency- and time-resolution
not achievable by traditional BIS systems.