Long-Term Modeling and Monitoring of Neuromusculoskeletal System Performance Using a Novel Skin-Compliant Epidermal Sensing System

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Skin-Compliant Epidermal Sensing System (ESS)

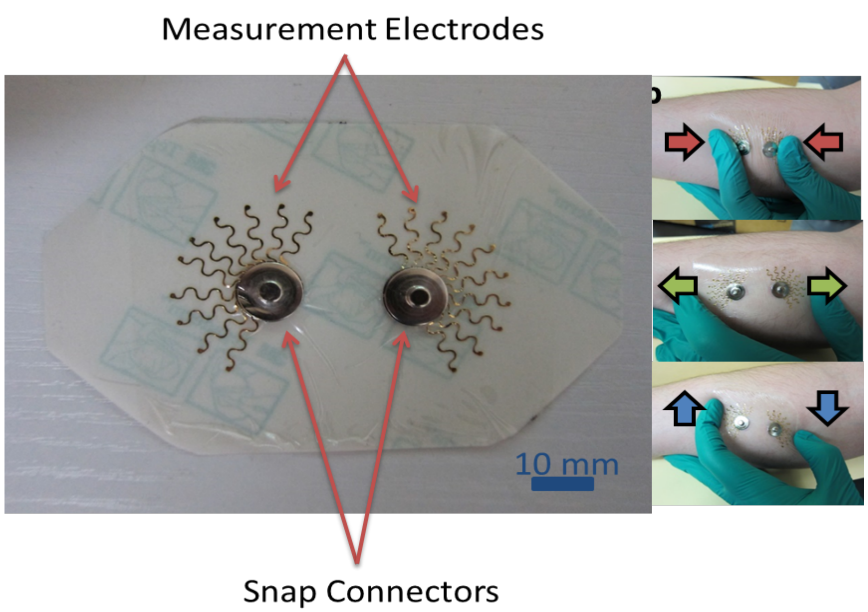


Figure 1: Tattoo-Like Sensor Geometry

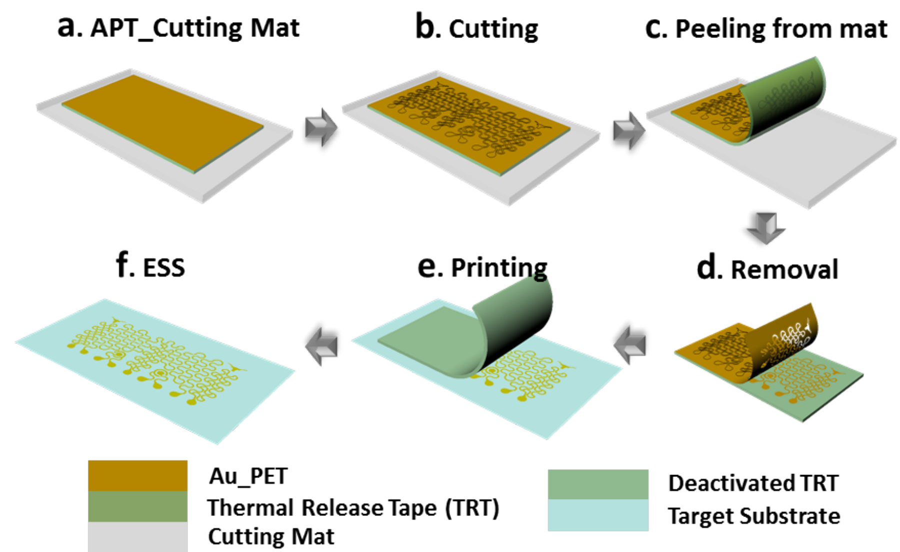


Figure 2: Cut-and-Print Manufacturing Process of New Sensor

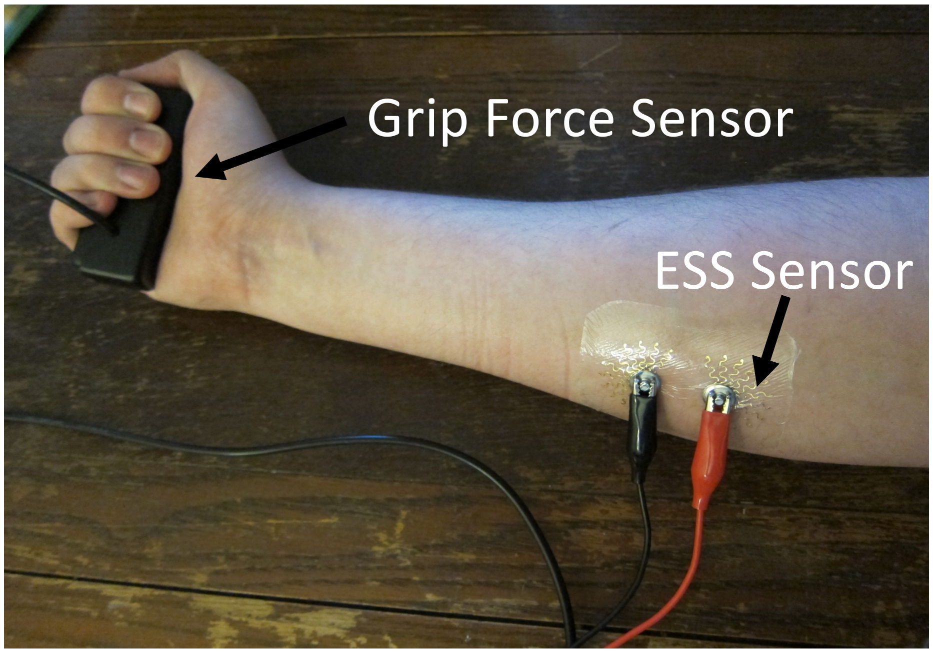


Figure 1: Experiment Set Up

Experiment Types:

- **Same-day repetitive fatigue trial**

2 mins for per trial X 8 ,30 mins rest time, one person

- **Multi-day repetitive fatigue trial**

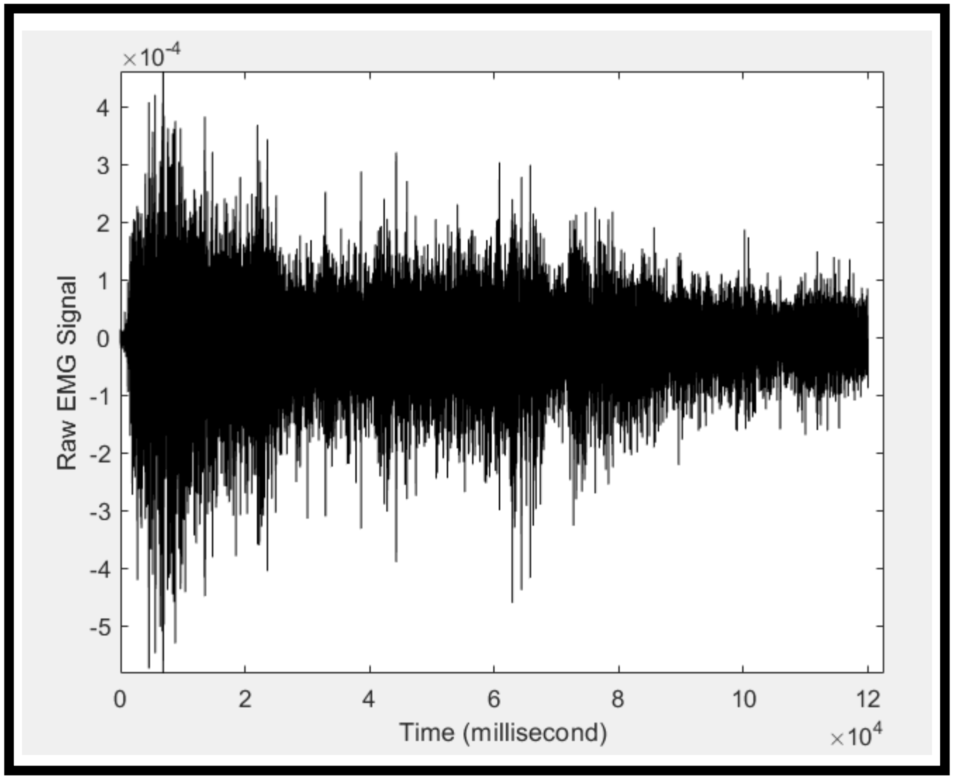
2 mins per trial, 2 trials per day in 3 consecutive days, one person

- **Repetitive Fatigue and recovery trial**

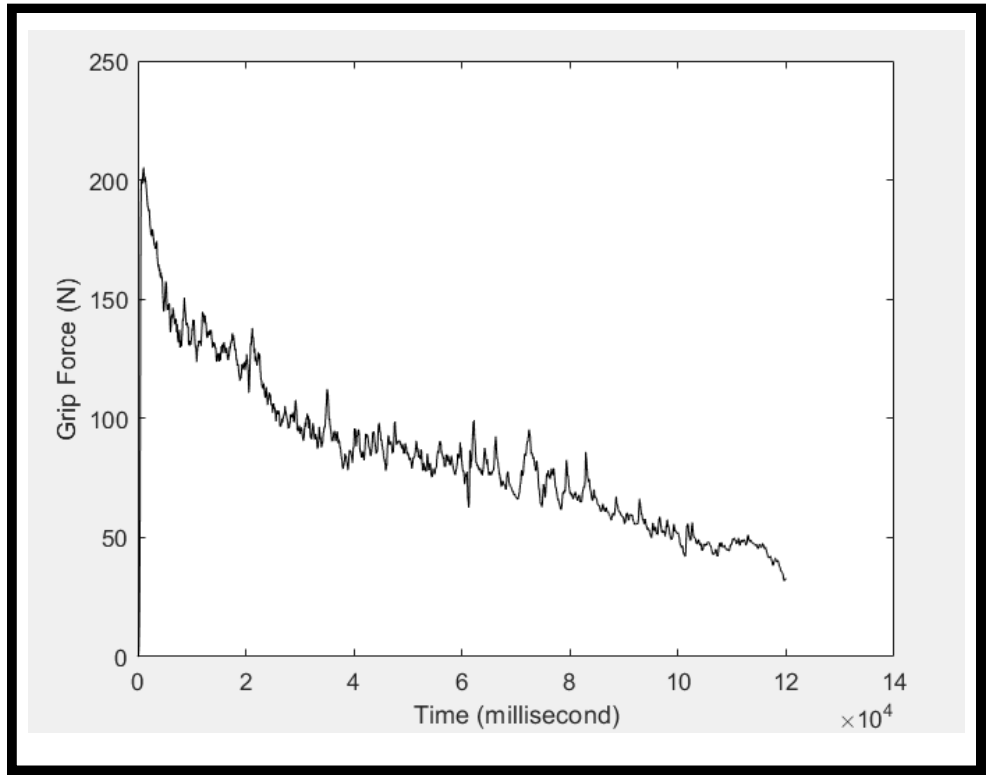
Gripping trial :2 mins X 3, 90 mins rest time

Recover detection trial : 10 secs X 9, 10 mins rest time

System Input: EMG 1000HZ



System Output: Grip Force 100HZ



Trial Code: C2016_04_24_Luke

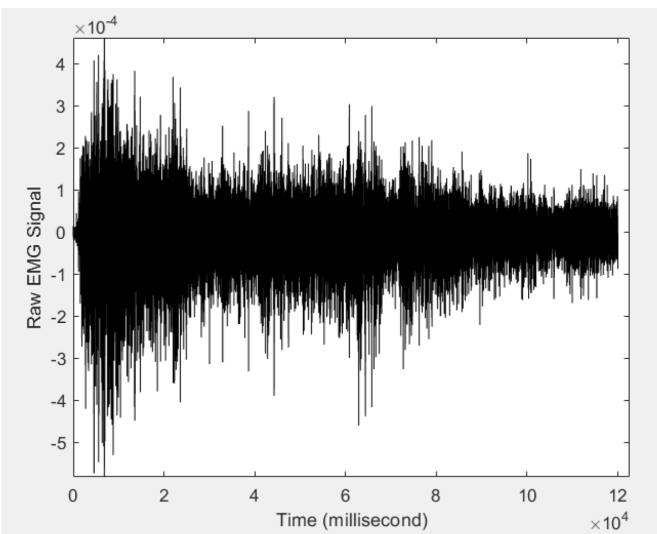
Data Processing on EMG signal

Raw EMG signal
$S(t)$

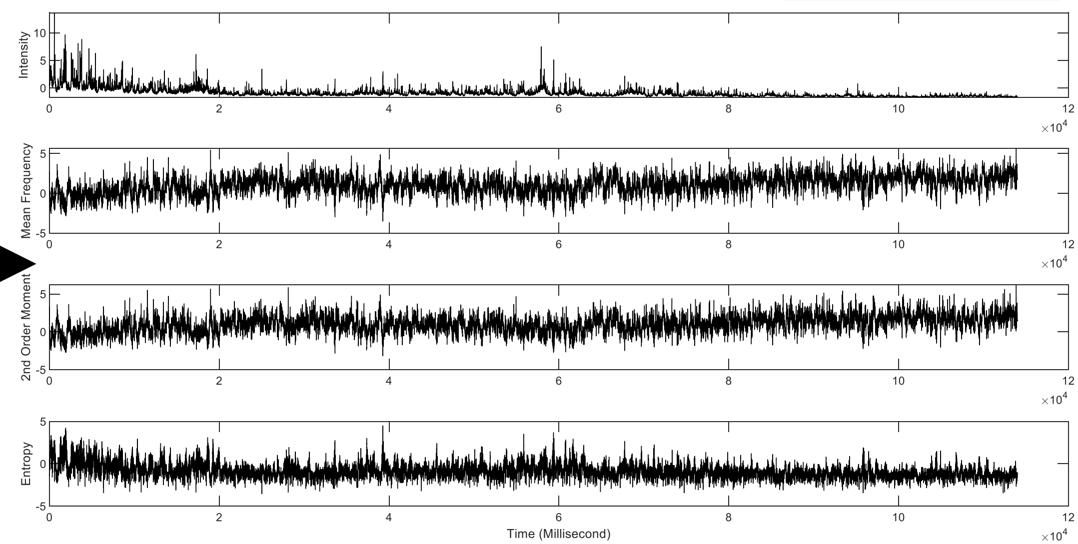
$$C(t,\omega)=\frac{1}{4\pi^2}\iiint s^*(u-\frac{1}{2}\tau)s(u+\frac{1}{2}\tau)\phi(\theta,\tau)e^{-j(\theta(t-u)+\tau\omega)}d\tau du d\theta$$

TF distribution of EMG
$C(t,\omega)$

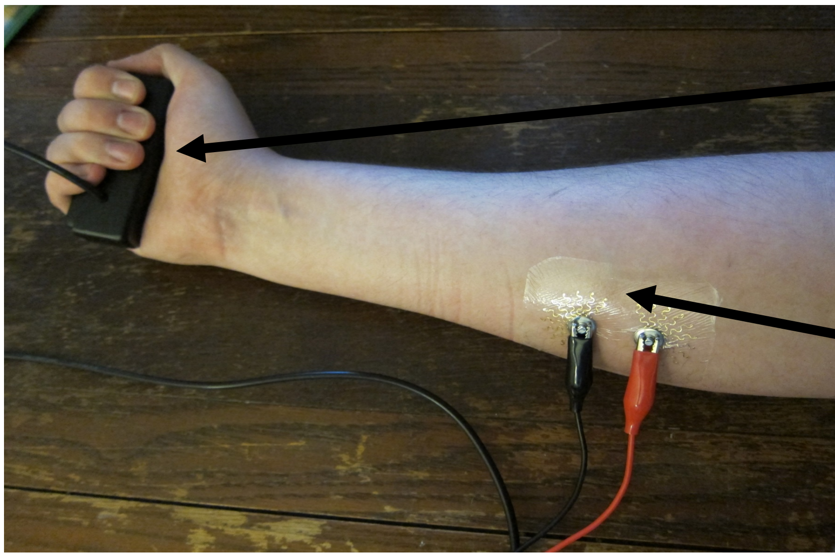
Intensity	$\int C(t,\omega)d\omega$
Mean Frequency	$\int \frac{C(t,\omega)}{<f^0\mid t>}\omega d\omega$
2nd Moment	$\int \frac{C(t,\omega)}{<f^0\mid t>}\omega^2 d\omega$
Entropy	$\int \frac{C(t,\omega)}{<f^0\mid t>}\ln\frac{C(t,\omega)}{<f^0\mid t>}d\omega$



Raw EMG Signal

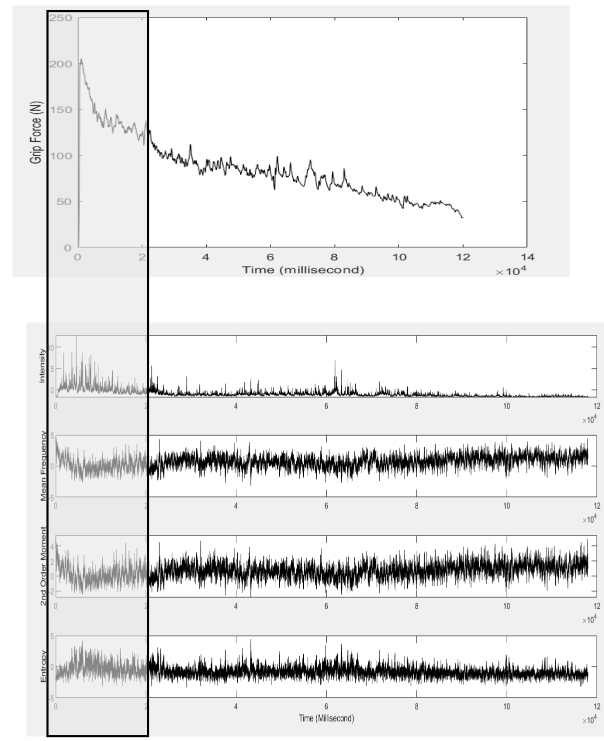


ARMAX Formulation



System Output : $F(t)$

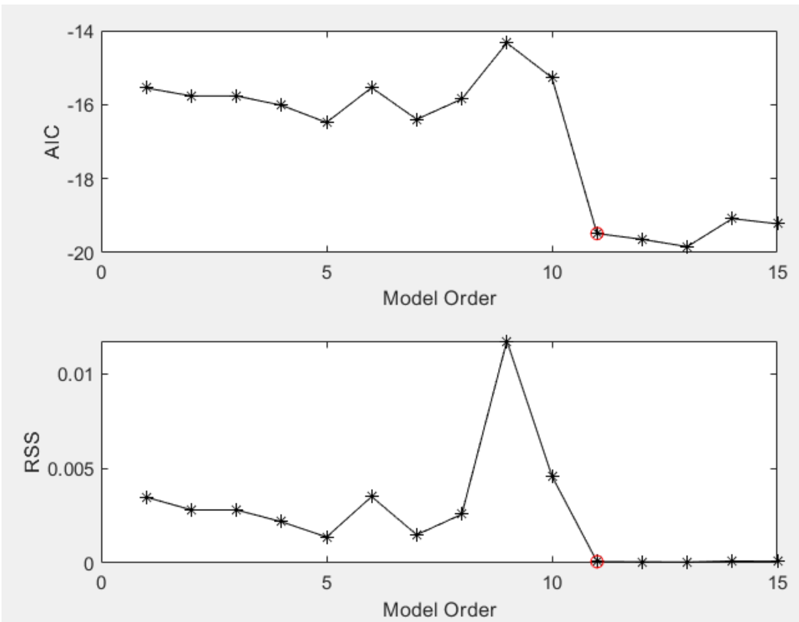
System Input : $\vec{X}(t) = \begin{bmatrix} f^0|t \\ f^1|t \\ f^2|t \\ E \end{bmatrix}$



$$F(t) = \sum_{n=1,2,\dots,N} \phi_n F(t-n) + \sum_{n=1,\dots,N-1} \theta_n a(t-n) + \vec{X}(t)$$

Modeling window: 20 seconds

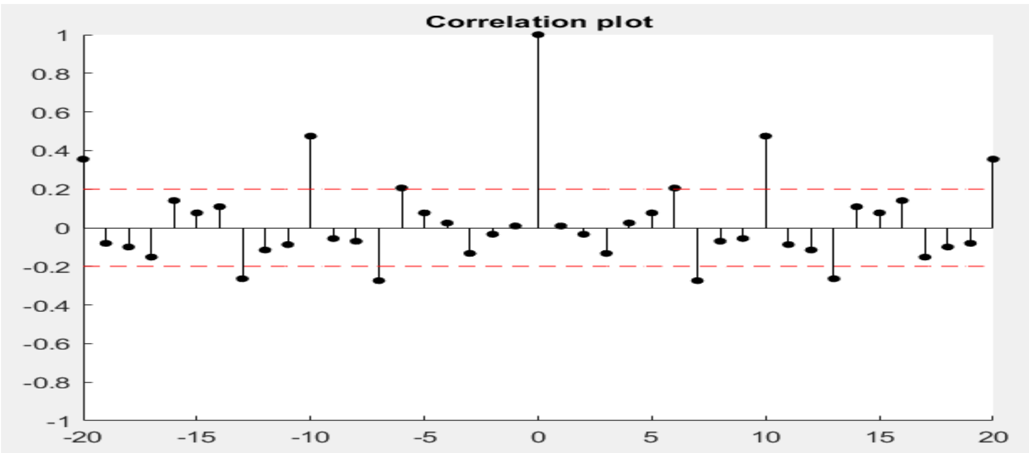
WHY??



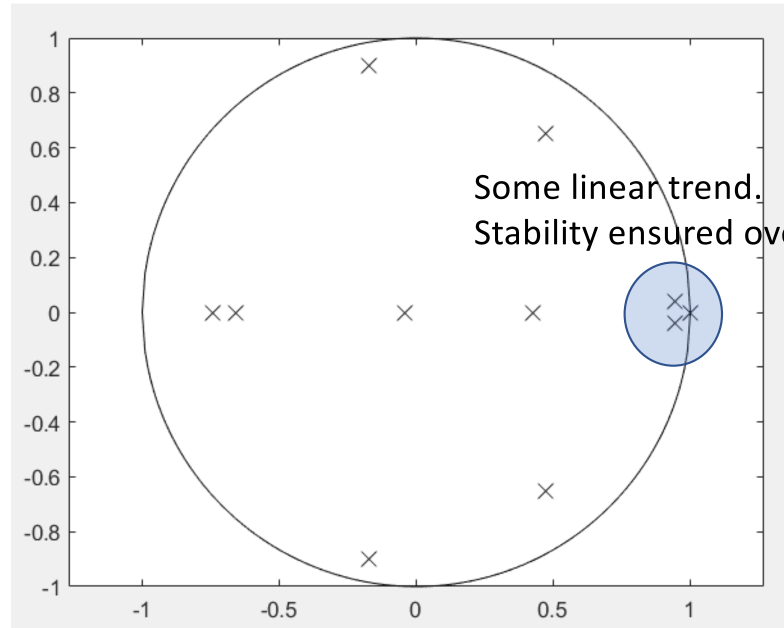
Model Order (11,12) for trial code:
‘C2016_04_24_Luke’

1) Set Initial ARMAX order (N,N-1) ←(2,1)
2) ***for*** $i \in \{1,2,3\}$ ***do***
3) ***If*** ARMAX($2\times i, 2\times i - 1$) vs ARMAX($2\times i + 2, 2\times i + 1$) can fix model order ***then***
4) Model order fixed← $\boldsymbol{True}$
5) ***else***
6) Model order fixed← $\boldsymbol{False}$
7) ***end if***
8) ***end for***
9) ***If*** $\sim$ Model order fixed ***then***
10) Compute AIC of model up to order N=15
11) Find $\tilde{n}\ s.t.: argmax\{AIC(\tilde{n}) - AIC(\tilde{n} - 1)\}$
12) Fix ARMAX model order as ARMAX ($\tilde{n}, \tilde{n} - 1$)
13) ***end if***
14) Check autocorrelation plot for adequacy

Model Evaluation



Lag vs Residual Correlation

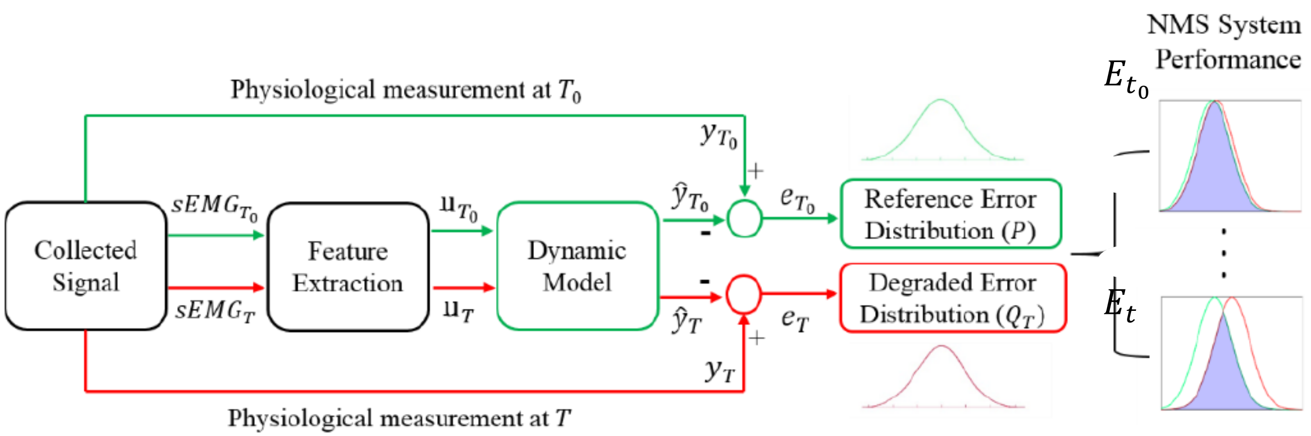


Poles Location

```
-0.1708 + 0.8983i
-0.1708 - 0.8983i
-0.7420 + 0.0000i
-0.6586 + 0.0000i
 0.4710 + 0.6497i
 0.4710 - 0.6497i
 1.0000 + 0.0000i
 0.9461 + 0.0409i
 0.9461 - 0.0409i
 0.4242 + 0.0000i
-0.0407 + 0.0000i
```

Model is OK consider a system sampled at 1000 HZ with extremely noise EMG input.

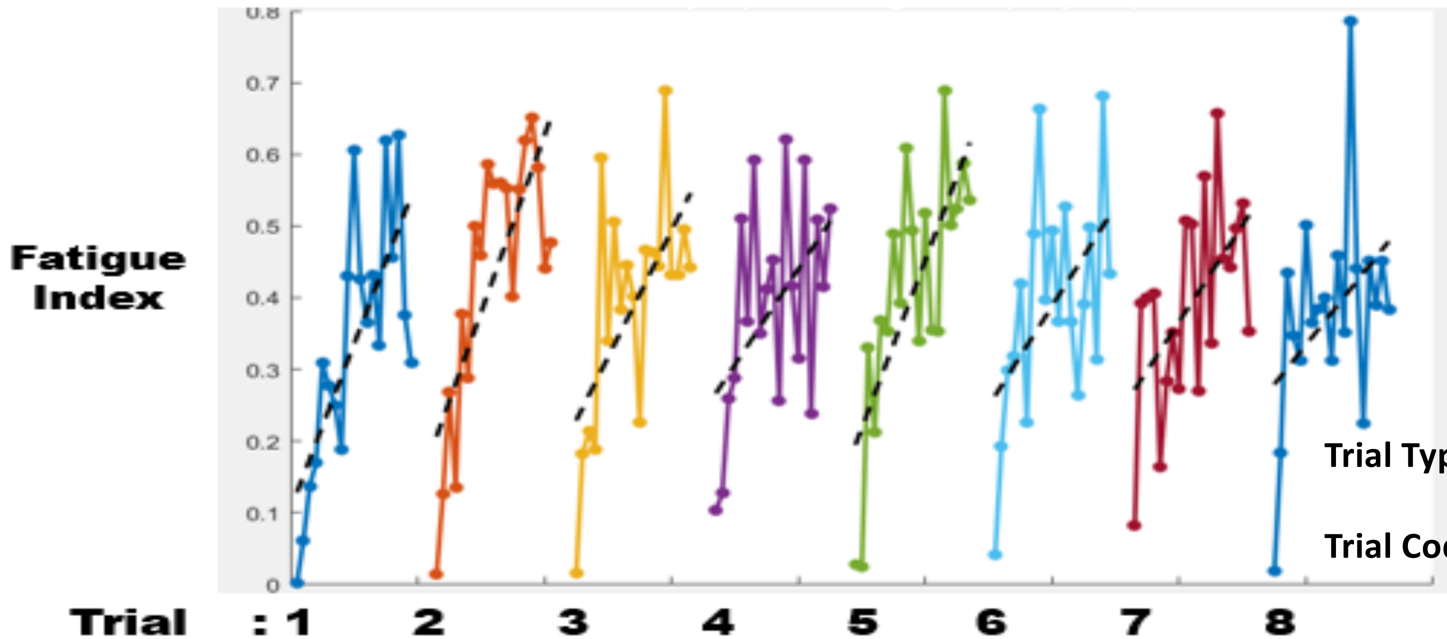
Fatigue Tracking



$$Fatigue\ Index\ (FI) \coloneqq D_{KL}\,(P||Q_T) = \sum_i P\,(i) \cdot \ln \frac{P(i)}{Q_T(i)}$$

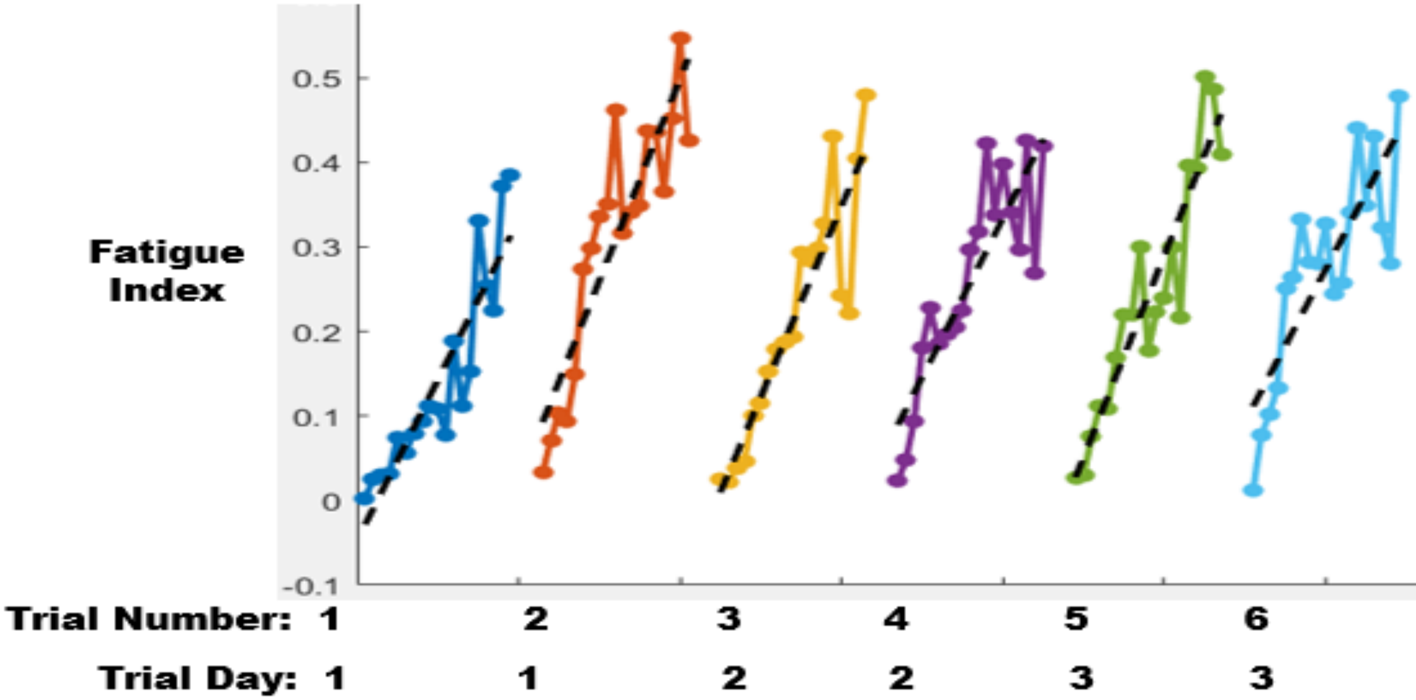
FI measures the similarity between current system condition and initial reference system.
FI close to zero means current system is similar to unfatigued system.
FI close to one means current system is different with unfatigued system.

Results



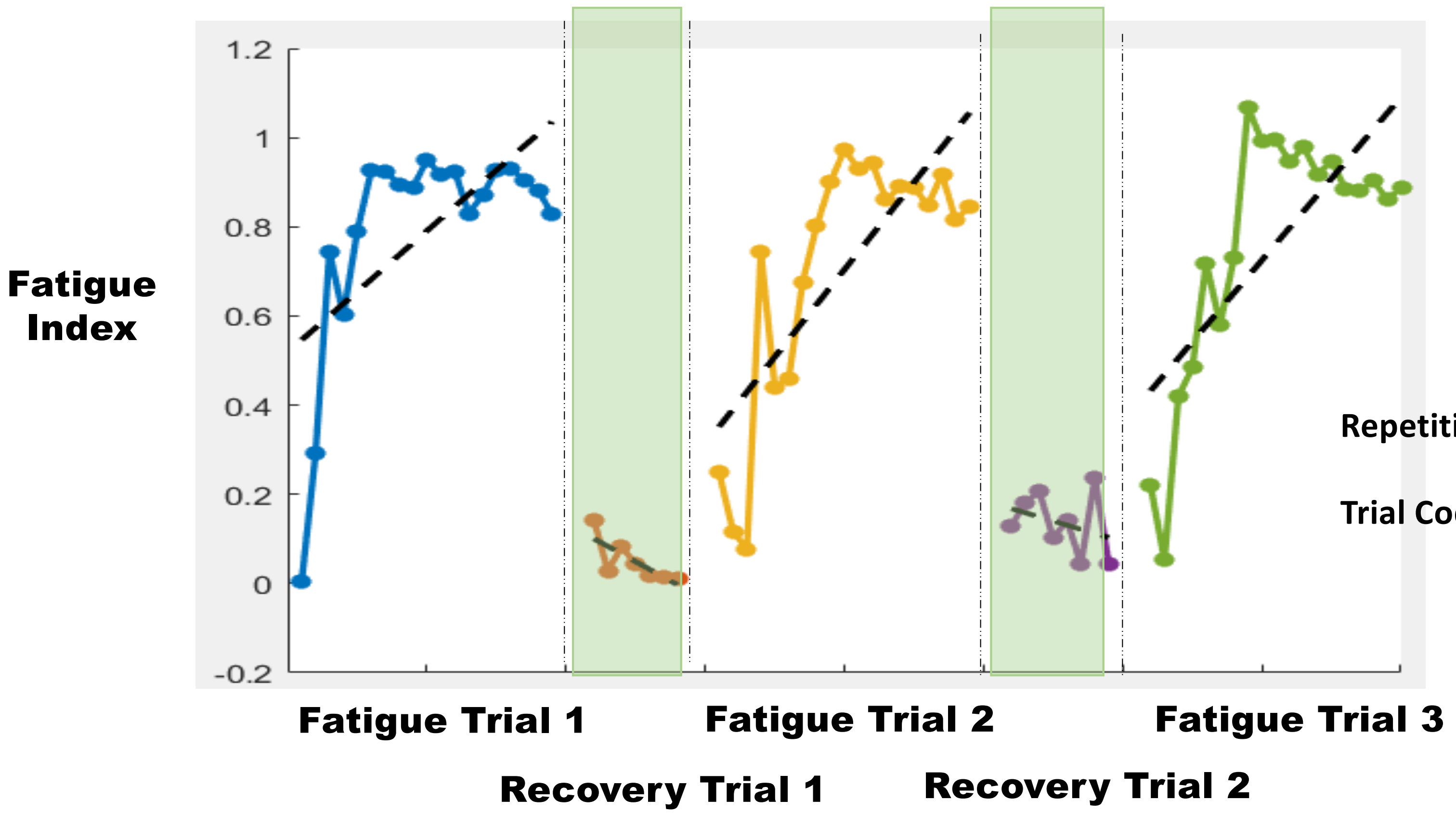
Trial Type: Same-day repetitive fatigue trial

Trial Code: D2016_08_31_Eric_ESSNET



Multi-day repetitive fatigue trial

Trial Code: IRENE_MULTI



Repetitive Fatigue and recovery trial

Trial Code: C2016_04_24_Luke

Conclusion:
High nonlinearity and noisy input and output causes residual correlation not close to zero.

By using an ARMAX Model we are able to model unfatigued human forearm neuromuscular dynamics and monitor fatigue as gripping continue.

Future Work:
Nonlinear neuromusculoskeletal system modeling with joint dynamics.