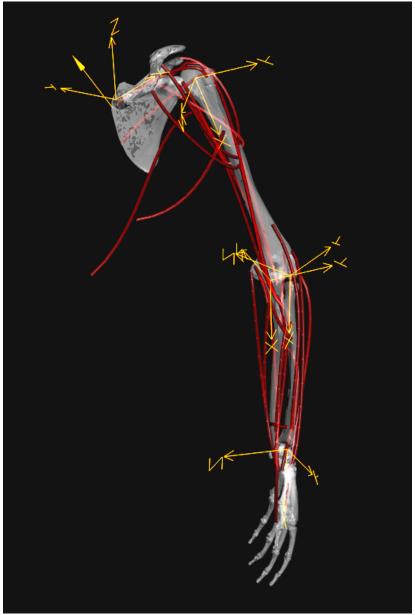
NUMERICAL MODELING: MULTIBODY

- Transfer functions may depend on several parameters, especially cockpit configuration
- Can only be obtained experimentally, from existing cockpit layouts: cost, time, complexity

- What about simulating pilot biodynamics?




Multibody model implemented in free, general purpose software MBDyn `http://www.mbdyn.org`



Each limb accounts for 6 rigid bodies:

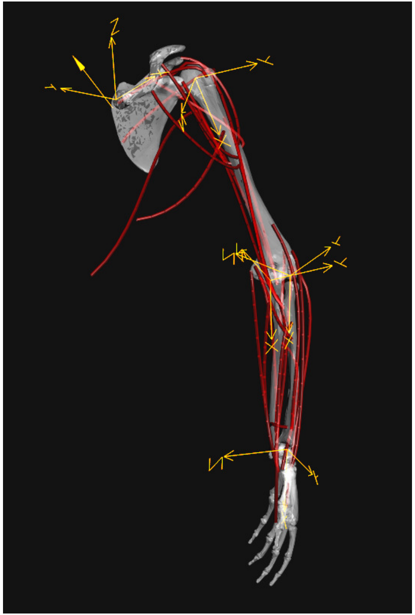
- Scapula
- Clavicle
- Humerus
- Radius
- Ulna
- Hand

For a total of 36 degrees of freedom.

The hand is considered as a single rigid body, as it is usually gripping the inceptor's handle.

28 muscles are modeled for each limb.

Multibody model implemented in free, general purpose software MBDyn `http://www.mbdyn.org`



Constraints:

- Scapulothoracic (ST): deformable, viscoelastic joint
- Sternoclavicular (SC): spherical joint (3)
- Acromioclavicular (AC): spherical joint (3)
- Glenhohumeral (GH): spherical joint (3)
- Humeroradial (HR): spherical joint (3)
- Humeroulnar (HU): revolute joint (5)
- Radioulnar (RU): point-on-line joint (2)
- Radiocarpal (RC): Cardano hinge (4)

13 degrees of freedom remain, per limb, after constraints are enforced.

Muscle Modeling: Hill-type 1D viscoelastic actuators: muscle and tendon passive behaviors are considered jointly in a Passive Elastic Element (PEE); pennation angles and cross-bridge elasticity are disregarded (Zajac, 1989).

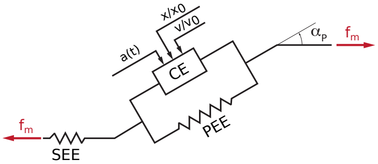
Force model by Pennestrì et al., 2008:

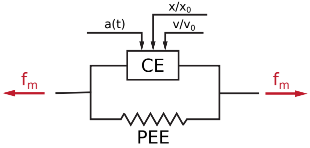
$$f_m(\overline{x},\overline{v},a) = f_{m0}\left(f_1(\overline{x})f_2(\overline{v})a(t) + f_3(\overline{x})\right)$$

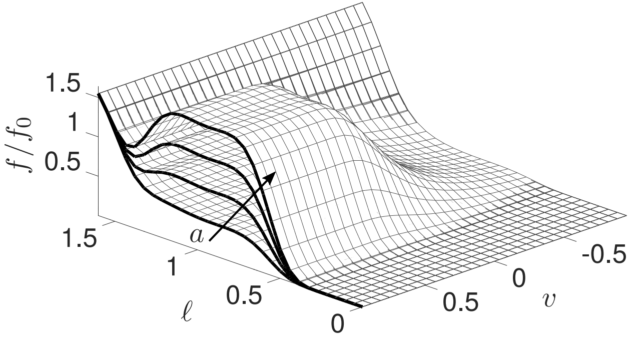
$$f_1(\overline{x}) = e^{\left(-40(\overline{x}-0.95)^4+(\overline{x}-0.95)^2\right)}$$

$$f_2(\overline{v}) = 1.6\left(1 - e^{\left(-1.1/(\overline{v}-1)^4+0.1/(\overline{v}-1)^2\right)}\right)$$

$$f_3(\overline{x}) = 1.3\tan^{-1}\left(0.1(\overline{x}-0.22)^{10}\right)$$



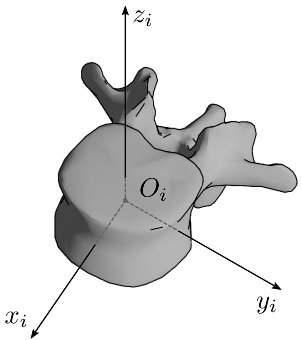


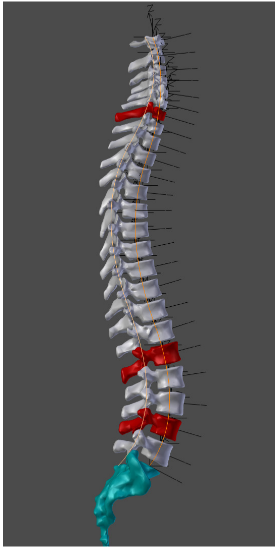


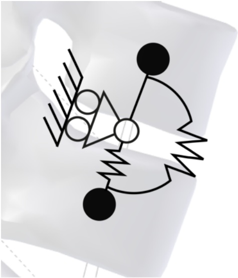
Multibody model implemented in free, general purpose software MBDyn (`http://www.mbdyn.org`)
It accounts for 35 rigid bodies:

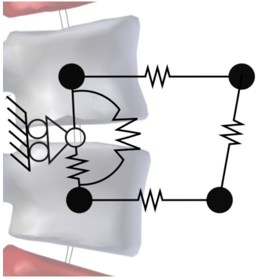
- head (1)
- cervical, thoracic and lumbar vertebrae (25)
- viscerae (8)
- the buttocks (1)

For a total of 210 unconstrained degrees of freedom.









Algebraic Constraints:

- Intervertebral: lateral and antero-posterior relative displacements constrained
- Vertebra-viscera: all relative rotations constrained
- Buttocks-Pelvis: all relative degrees of freedom except relative vertical displacement and rotation about lateral axis

79 degrees of freedom remain after constraints are enforced.

Internal forces:

- Intervertebral: linear viscoelastic elements acting on relative axial displacements, rotational viscoelastic elements acting on all relative rotations;
- Vertebra-viscera: linear viscoelastic elements acting on all relative displacements;
- Viscera-viscera: linear viscoelastic elements acting on all relative displacements;
- Buttocks-Pelvis: 6D linear viscoelastic element acting on all relative displacements/rotations;

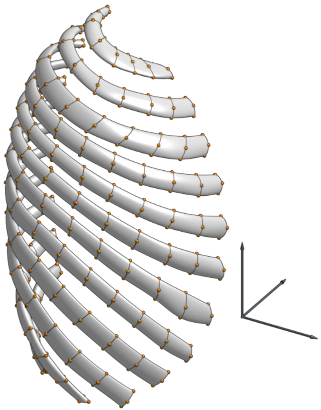
(initial) Parameters values taken from literature (Kitazaki et al., 1997, Valentini et al. 2016)

Preprocessing:

1. generate geometrical and inertial properties of segments
2. define initial pose (static model)

Solution phases:

1. Inverse kinematics: penalty approach, focus on ergonomy
2. Inverse dynamics
3. Estimation of muscular activation: optimization seeking minimal total activation / minimal metabolic cost / minimal total muscle force
4. Direct analysis: reflexive part of activation estimated and imposed, interaction with full vehicle model is evaluated



Since we operate in a virtual prototyping framework, we cannot rely on subject specific definition of parameters.

The generation of the parameters is based on statistical models:

1. full ribcage model by Shi et al.

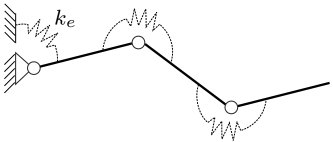
$$\mathbf{g} = \overline{\mathbf{g}} + \mathbf{P} \cdot \mathbf{C} \cdot \mathbf{f} \qquad (1)$$

   with $\mathbf{f} = \begin{bmatrix} a & s & b & g & 1 \end{bmatrix}^T$
   - $a = \text{age}$
   - $s = \text{stature}$
   - $b = \text{BMI}$
   - $g = \text{gender}$
2. linear regression equations for segment lengths (e.g. [Cheverud et al., 1990])
3. scaling equations for segments inertial parameters ([McConville et al., 1980, Dumas et al., 2007])

Imposed kinematics, from ergonomy and task-dependent considerations:

1. Head orientation (3 d.o.f)
2. C1 vertically aligned with Pelvis/First “non supported” thoracic vertebra (2 d.o.f)

The system is characterized by a high degree of kinematic redundancy.
Direct solution at position level, penalty approach.



$$\min J_p(\mathbf{x}) = \frac{1}{2}\left(\boldsymbol{\theta}-\boldsymbol{\theta}_e\right)^T \mathbf{K}_e\left(\boldsymbol{\theta}-\boldsymbol{\theta}_e\right) + \boldsymbol{\lambda}^T\boldsymbol{\phi} + \boldsymbol{\mu}^T\left(\boldsymbol{\psi}(\mathbf{x}) - \boldsymbol{\alpha}(t)\right)$$

$$\min J_v(\dot{\mathbf{x}}) = \frac{1}{2}\left(\dot{\mathbf{x}}-\dot{\mathbf{x}}_{\text{ref}}\right)^T \mathbf{M}\left(\dot{\mathbf{x}}-\dot{\mathbf{x}}_{\text{ref}}\right) + \boldsymbol{\lambda}^T\boldsymbol{\phi}_{/\mathbf{x}}\dot{\mathbf{x}} + \boldsymbol{\mu}^T\left(\boldsymbol{\psi}_{/\mathbf{x}}\dot{\mathbf{x}} - \dot{\boldsymbol{\alpha}}(t)\right)$$

$$\min J_a(\ddot{\mathbf{x}}) = \frac{1}{2}\left(\ddot{\mathbf{x}}-\ddot{\mathbf{x}}_{\text{ref}}\right)^T \mathbf{M}\left(\ddot{\mathbf{x}}-\ddot{\mathbf{x}}_{\text{ref}}\right) + \boldsymbol{\lambda}^T\left(\boldsymbol{\phi}_{/\mathbf{x}}\ddot{\mathbf{x}} + \left(\boldsymbol{\phi}_{/\mathbf{x}}\dot{\mathbf{x}}\right)_{/\mathbf{x}}\right) + \boldsymbol{\mu}^T\left(\boldsymbol{\psi}_{/\mathbf{x}}\ddot{\mathbf{x}}\left(\boldsymbol{\psi}_{/\mathbf{x}}\dot{\mathbf{x}}\right)_{/\mathbf{x}}\right)$$

The spine vertebra-vertebra internal elastic elements contribute to the total potential energy that is minimized during the kinematics inversion.

Baseline Activation

Once the kinematics is fully known, joint torques can be computed

$$\mathbf{c} = \left(\boldsymbol{\theta}^{+}_{/\mathbf{x}}\right)^{T} \left(\mathbf{M}\ddot{\mathbf{q}} - \mathbf{f}\right)$$

Torques are, in turn, produced by a redundant set of muscle actuators. Therefore an optimization problem is solved, seeking the related activations

$$\min J(\mathbf{a}) = \frac{1}{4}\mathbf{a}^{T} \left(\mathbf{a}^{T}\mathbf{W}'\mathbf{a}\right) \mathbf{a} + \frac{1}{2}\mathbf{a}^{T}\mathbf{W}''\mathbf{a}$$

s.t.

$$\mathbf{c} = \left(\boldsymbol{\theta}^{+}_{/\mathbf{x}}\right)^{T} \mathbf{B}\mathbf{f}_{m}\left(\overline{x}, \overline{v}, a\right)$$

$$0 < a_i < 1$$

However, matrix $\mathbf{A} = \left(\boldsymbol{\theta}^{+}_{/\mathbf{x}}\right)^{T}$ is rectangular and can be therefore decomposed, for example with SVD:

$$\mathbf{A} = \mathbf{U}\boldsymbol{\Sigma}\mathbf{V}^{T} = \left[\mathbf{U}\right]\left[\boldsymbol{\Sigma} \quad \mathbf{O}\right]\begin{bmatrix}\mathbf{V}^{T}_{\mathbf{TAM}} \\ \mathbf{V}^{T}_{\mathbf{TLAM}}\end{bmatrix} \qquad (2)$$

Highlighting the presence of Torque-Less Activation Modes.

The baseline activation, directly depending on the torques required to perform a task, does not take into account the impedance control of the Central Nervous System.

Two contributions are introduced for this purpose:

1. TLAMs: a linear combination $\mathbf{b}\mathbf{V}_{\text{TLAM}}$ is sought by solving

$$\min J(\mathbf{b}) = \frac{1}{2}\mathbf{b}^T\mathbf{W}'''\mathbf{b}$$
$$\text{s.t.}$$
$$0 < a_i < 1$$

2. reflexive activation: linearized, quasi-steady approximation of this contribution is introduced:

$$a_r = k_p\left(\frac{x}{x_0} - \frac{x_{\text{ref}}}{x_0}\right) + k_d\left(\frac{\dot{x}}{v_0}\right)$$

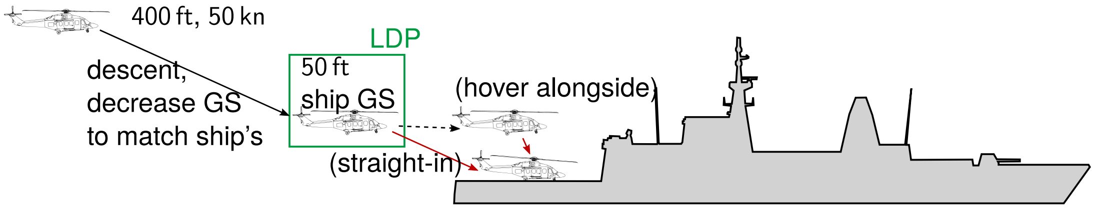
The total activation, for all muscles, therefore is (calling $\mathbf{a}_0$ the baseline contribution):

$$\mathbf{a} = \mathbf{a}_0 + \mathbf{K}_{\text{TLAM}}\mathbf{V}_{\text{TLAM}}\mathbf{b} + \mathbf{a}_r$$

EXPERIMENTAL ACTIVITIES

Test Campaign:

- facility: Leonardo Helicopters Division fixed-base helicopter flight simulator AWARE
- tested scenario: medium weight helicopter (AW169/AW129) deck landing on frigate ship (Bergamini class)
- pilot: experienced, ex-navy test pilot



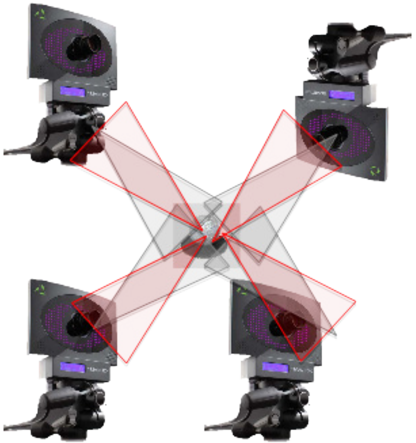
Objectives:

1. identify typical muscular activation patterns
2. search for correlation perceived and measured pilot workload and task difficulty
3. validate and improve pilot biomechanical (multibody) models

Motion Capture

System composed by 8 NIR cameras that capture the motion of 9 reflective markers:

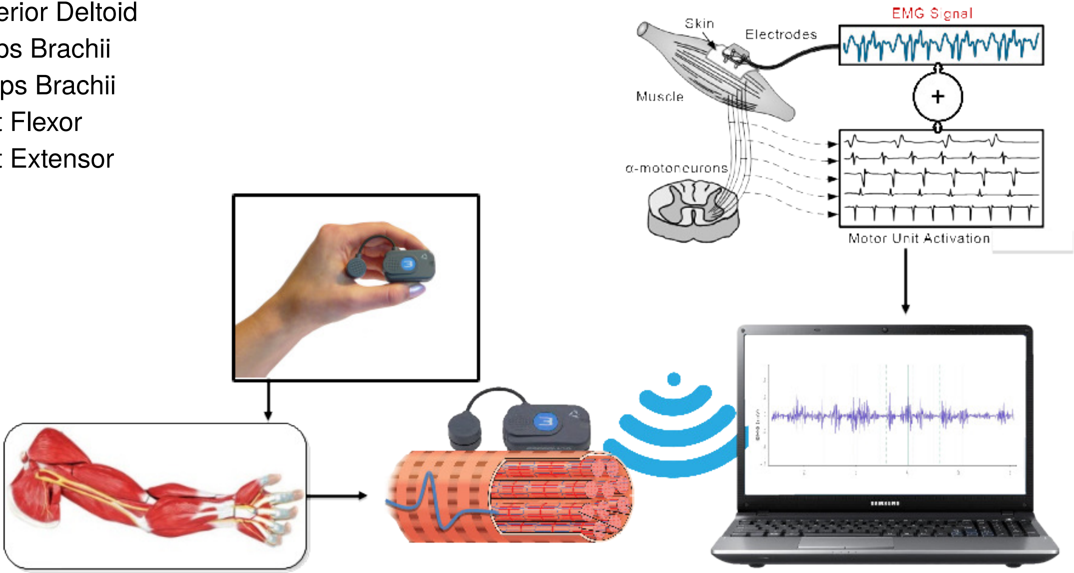
1. sternum (manubrium)
2. R acromion
3. R lateral elbow
4. R medial wrist
5. L acromion
6. L lateral elbow
7. L medial elbow
8. L lateral wrist
9. L medial wrist

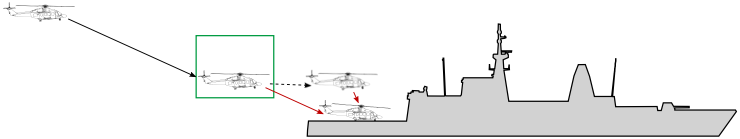


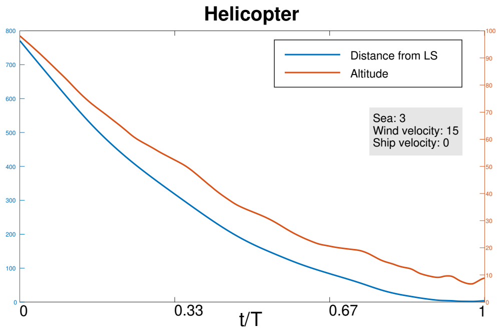
EMG measurements

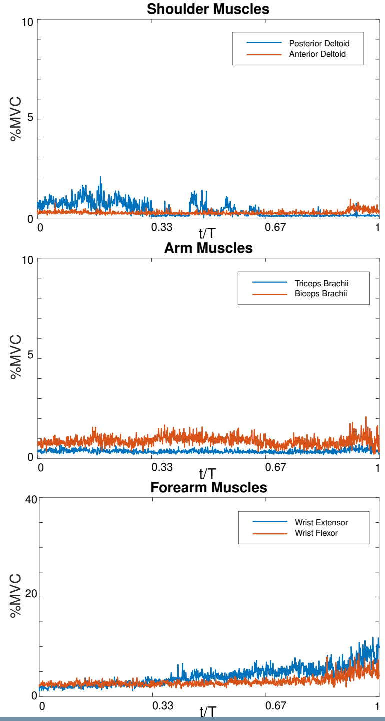
6 Electromiography sensors:

1. L Anterior Deltoid
2. L Posterior Deltoid
3. L Biceps Brachii
4. L Triceps Brachii
5. L Wrist Flexor
6. L Wrist Extensor









Early results show some consistent patterns:

- EMG activity concentrated in forearm muscles (pilot experience?)
- EMG activity increases with inverse distance from landing spot

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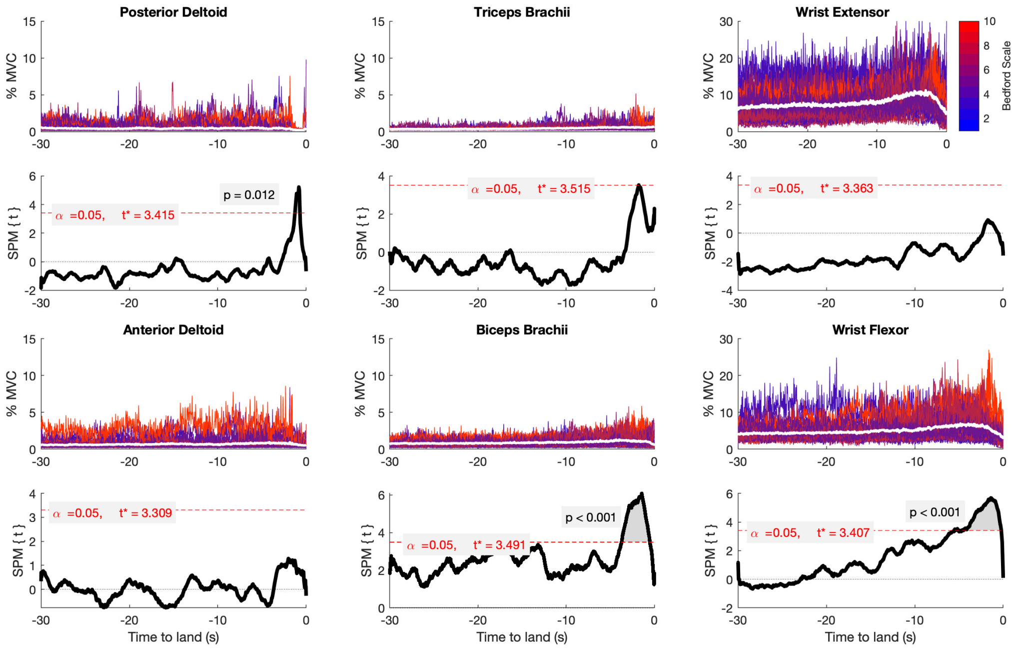
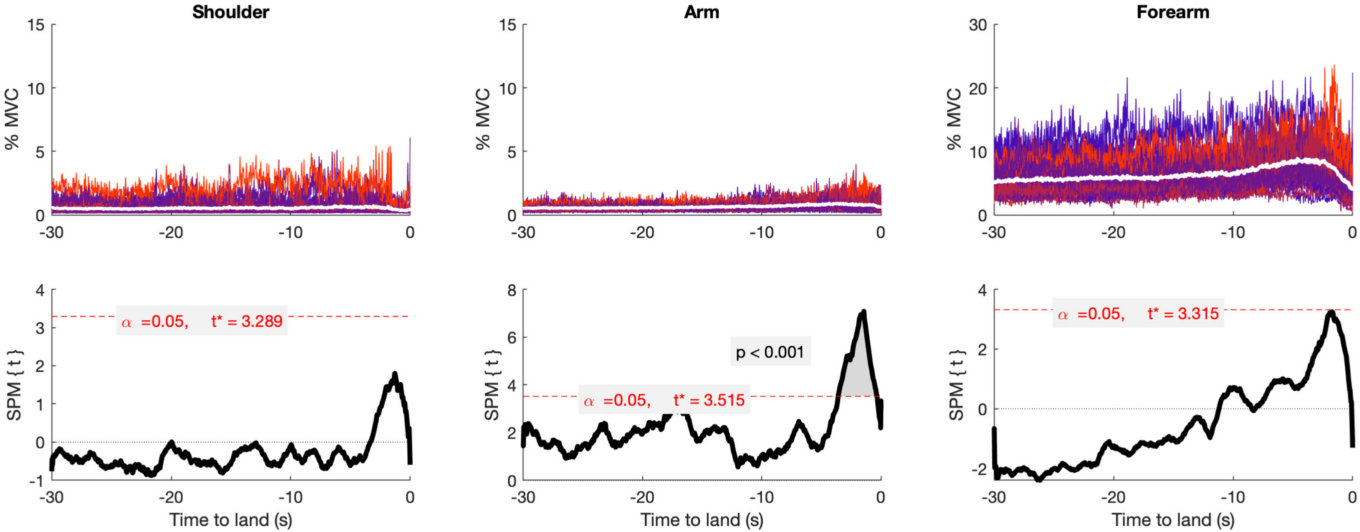
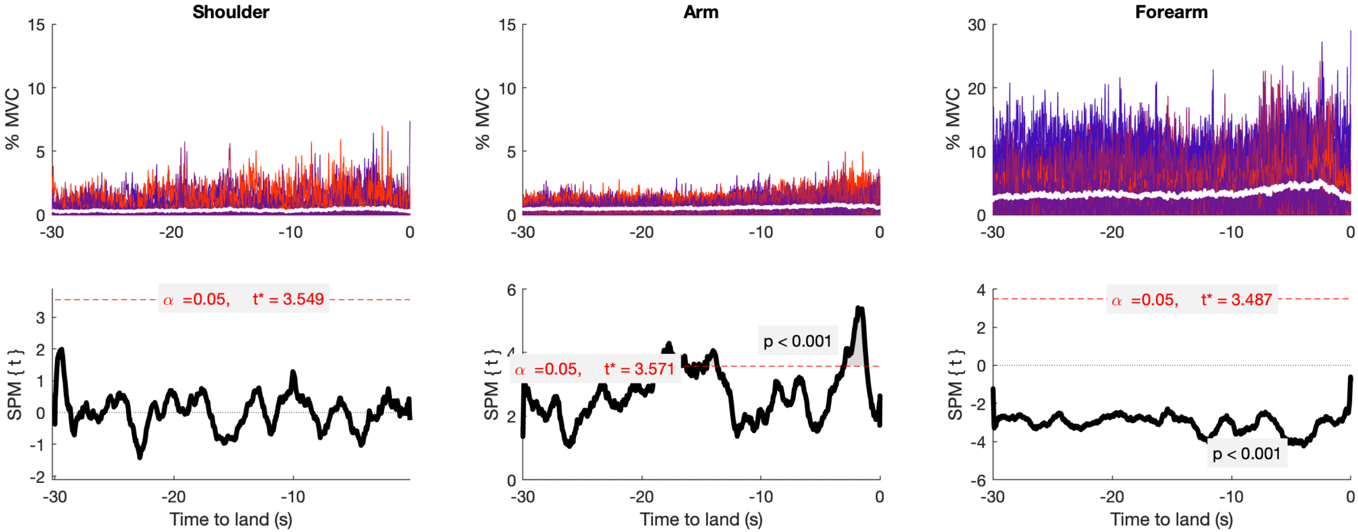
Statistical Parameter Mapping (SPM) analysis: individual muscles EMG activity vs Bedford score



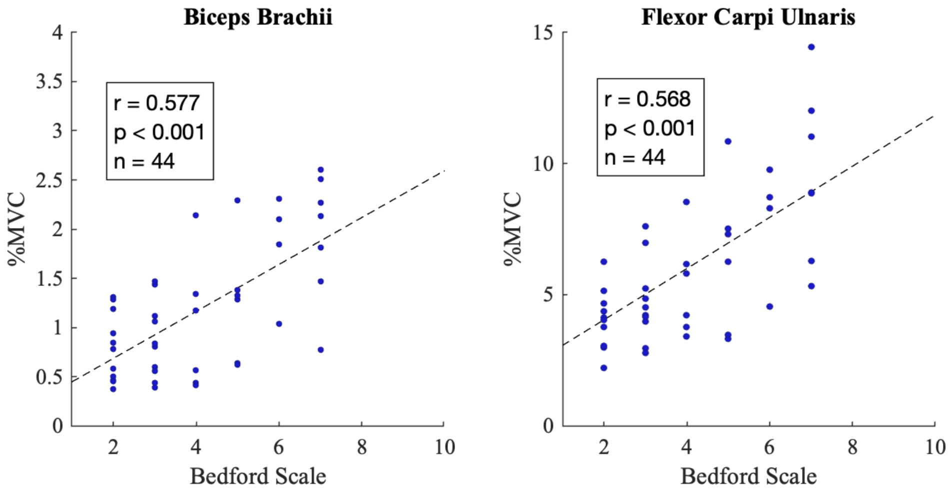
Statistical Parameter Mapping (SPM) analysis: average EMG activity of limb section vs Bedford score



Statistial Parameter Mapping (SPM) analysis: difference of EMG activity of limb section vs Bedford score



Linear regression on average EMG activity in correlated time window vs Bedford score



Modeling fallbacks:

1. choice and weighting of objective function in baseline activation computation

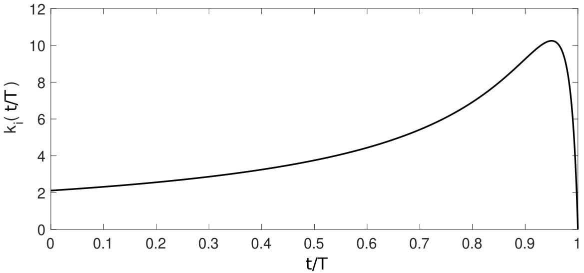
$$J(\mathbf{a}_0) = \frac{1}{4}\mathbf{a}_0^T\left(\mathbf{a}_0^T\mathbf{F_0}\mathbf{a}_0\right)\mathbf{a}_0 + \frac{1}{2}\mathbf{a}_0^T\mathbf{F_0}\mathbf{a}_0$$

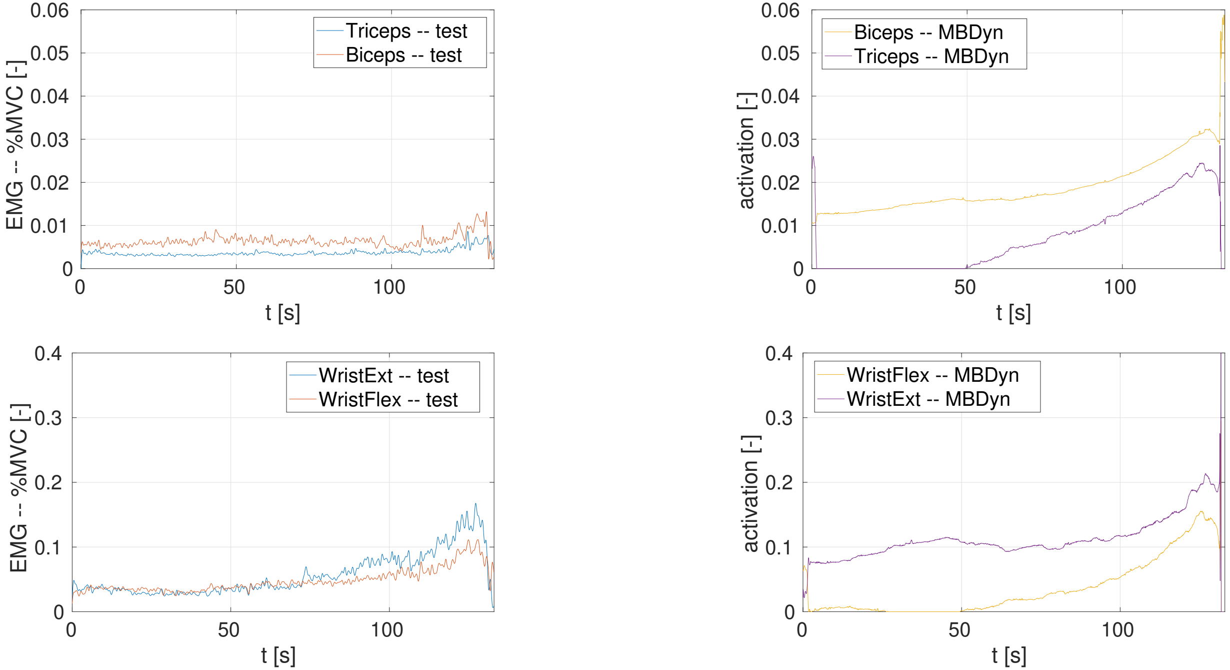
2. choice of TLAMs that favours activation level increase in forearm muscles

$$J(\mathbf{b}) = \frac{1}{2}\mathbf{b}^T\mathbf{F}_0\mathbf{b}$$

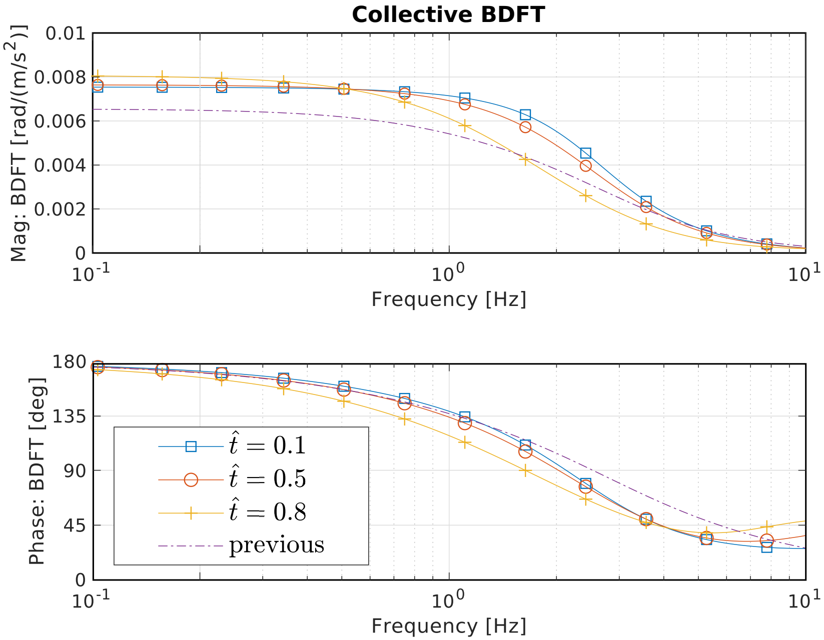
3. use of time-to-target (Padfield, 2011) concepts in gain scheduling for TLAMs and reflexive contributions to activation

$$\mathbf{a} = \mathbf{a}_0 + \mathbf{K}(\tau)\left(\mathbf{V}_{\text{TLAM}}\mathbf{b} + \mathbf{a}_r\right)$$




Triceps -- test
Biceps -- test
EMG -- %MVC [-]
t [s]
Biceps -- MBDyn
Triceps -- MBDyn
activation [-]
t [s]
WristExt -- test
WristFlex -- test
EMG -- %MVC [-]
t [s]
WristFlex -- MBDyn
WristExt -- MBDyn
activation [-]
t [s]

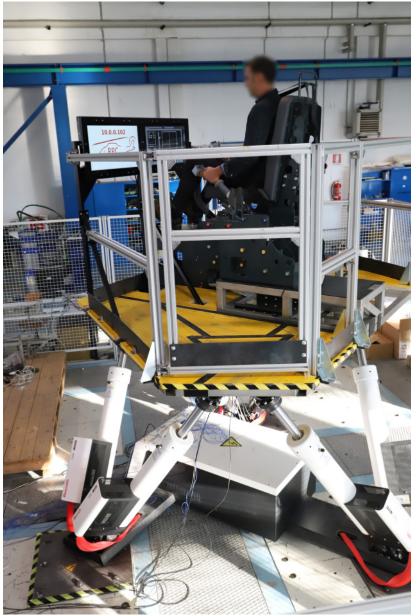
BDFTs estimated with multibody model:



THE RPC TESTBED @DAER

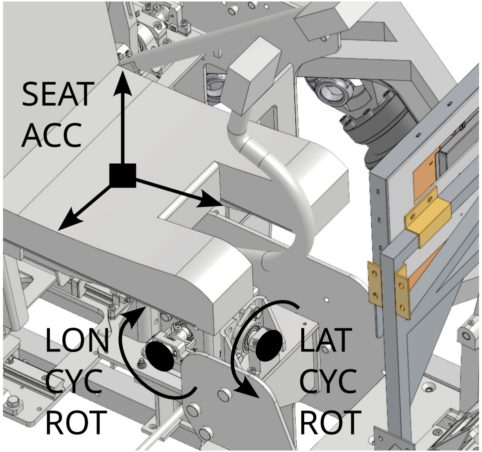
RPC Test-bed: composed by:

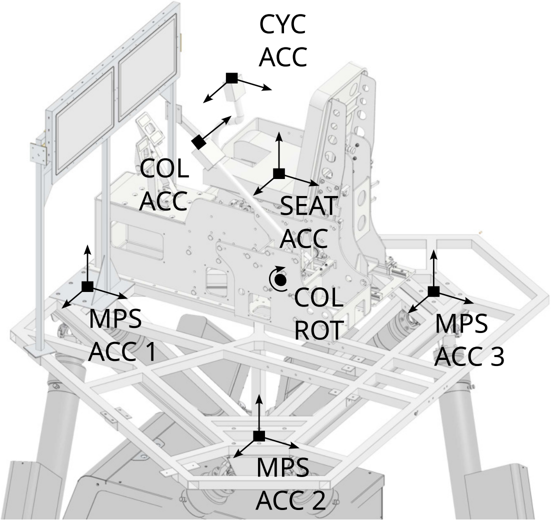
1. a 6-DOF Motion Platform System (MPS) Bosch eMotion 1500;



RPC Test-bed: composed by:

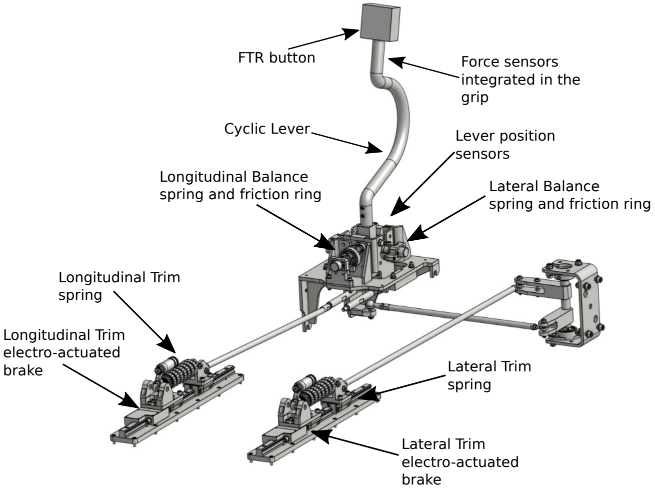
1. a 6-DOF Motion Platform System (MPS) Bosch eMotion 1500;
2. a customized measurement system;

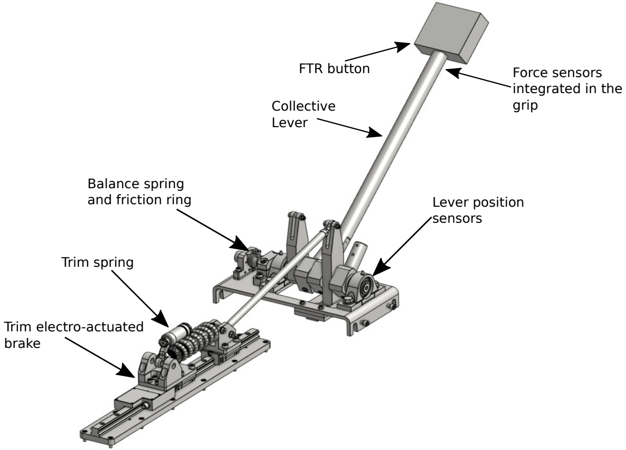


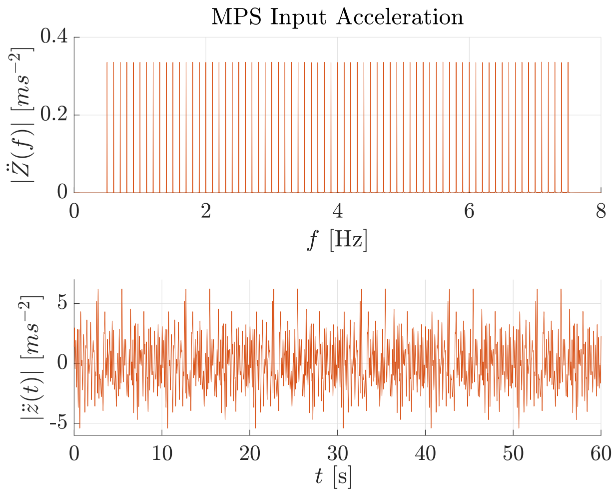


RPC Test-bed: composed by:

1. a 6-DOF Motion Platform System (MPS) Bosch eMotion 1500;
2. a customized measurement system;
3. a reconfigurable cockpit mock-up.



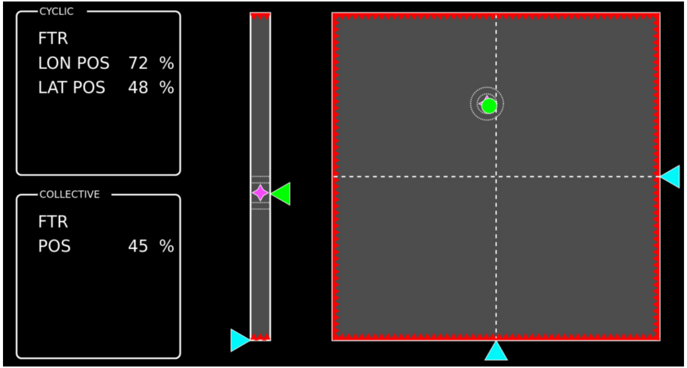


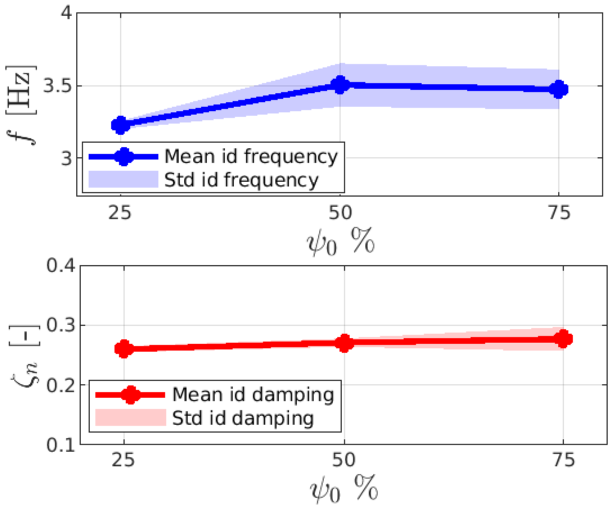


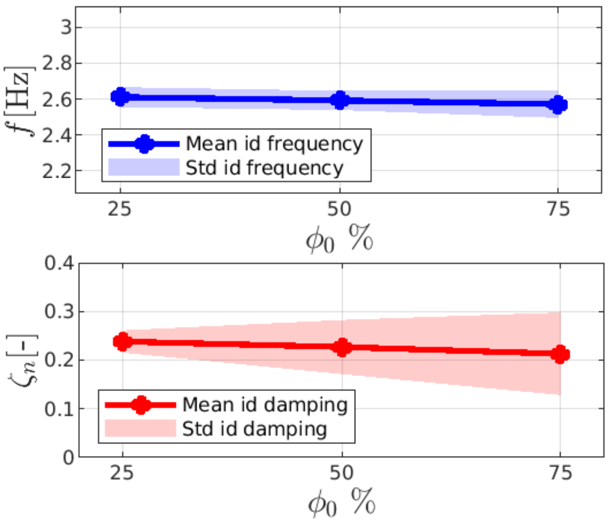
The pilot-vehicle system is excited by a pseudo-random waveform in the frequency band $[1, 7.5]$ hertz with limited RMS acceleration level:

- $1\,\mathrm{m\,s^{-2}}$ for the vertical axis acceleration $\ddot{z}(t)$;
- $0.5\,\mathrm{m\,s^{-2}}$ for the lateral axis acceleration $\ddot{y}(t)$;
- $1.5\,\mathrm{m\,s^{-2}}$ for the longitudinal axis acceleration $\ddot{x}(t)$;

while the pilot is asked to perform a simple tracking task.

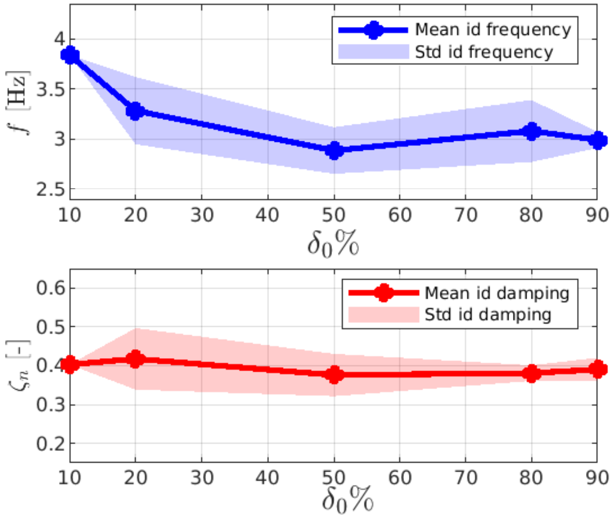




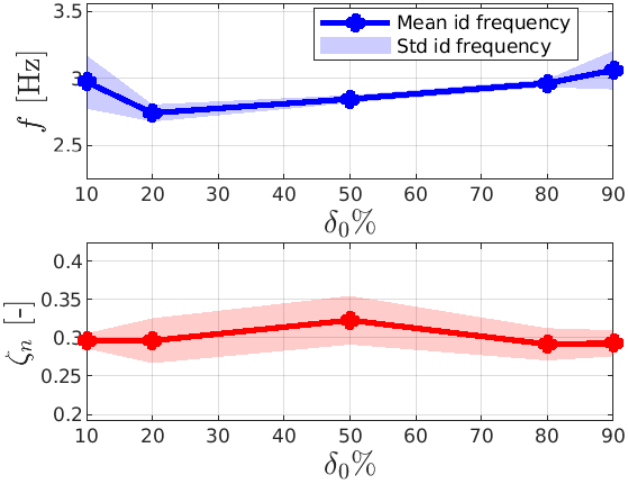


Mean and standard deviation of the identified frequency and damping at different longitudinal cyclic lever position. Input longitudinal acceleration. Output: longitudinal cyclic rotation.

Mean and standard deviation of the identified frequency and damping at different lateral cyclic lever position. Input: lateral acceleration. Output: lateral cyclic rotation.



Mean and standard deviation of the identified frequency and damping at different collective lever position using light short collective (1.21 kg, 350 mm) stick. Input: vertical acceleration $\ddot{Z}$. Output: collective rotation δ.



Mean and standard deviation of the identified frequency and damping at different collective lever position using heavy, long collective. (3.03 kg, 800 mm) Input: vertical acceleration $\ddot{Z}$. Output: collective rotation δ.

Conclusions

- Understanding of PVI & A/RPC
- Modeling of pilot's BDFT and NMA
- Understanding of aeroelastic RPC phenomena
- Biomechanical pilot modeling
- Correlation with experiments

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Future work

- Biomechanical modeling for BDFT/NMA prediction of novel configurations
- Evolve RPC testbed into RPC-capable Flight Sim
- Develop design guidelines for RPC-free configurations