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Applying complementary energy methods to estimate ground reaction forces of an exoskeleton

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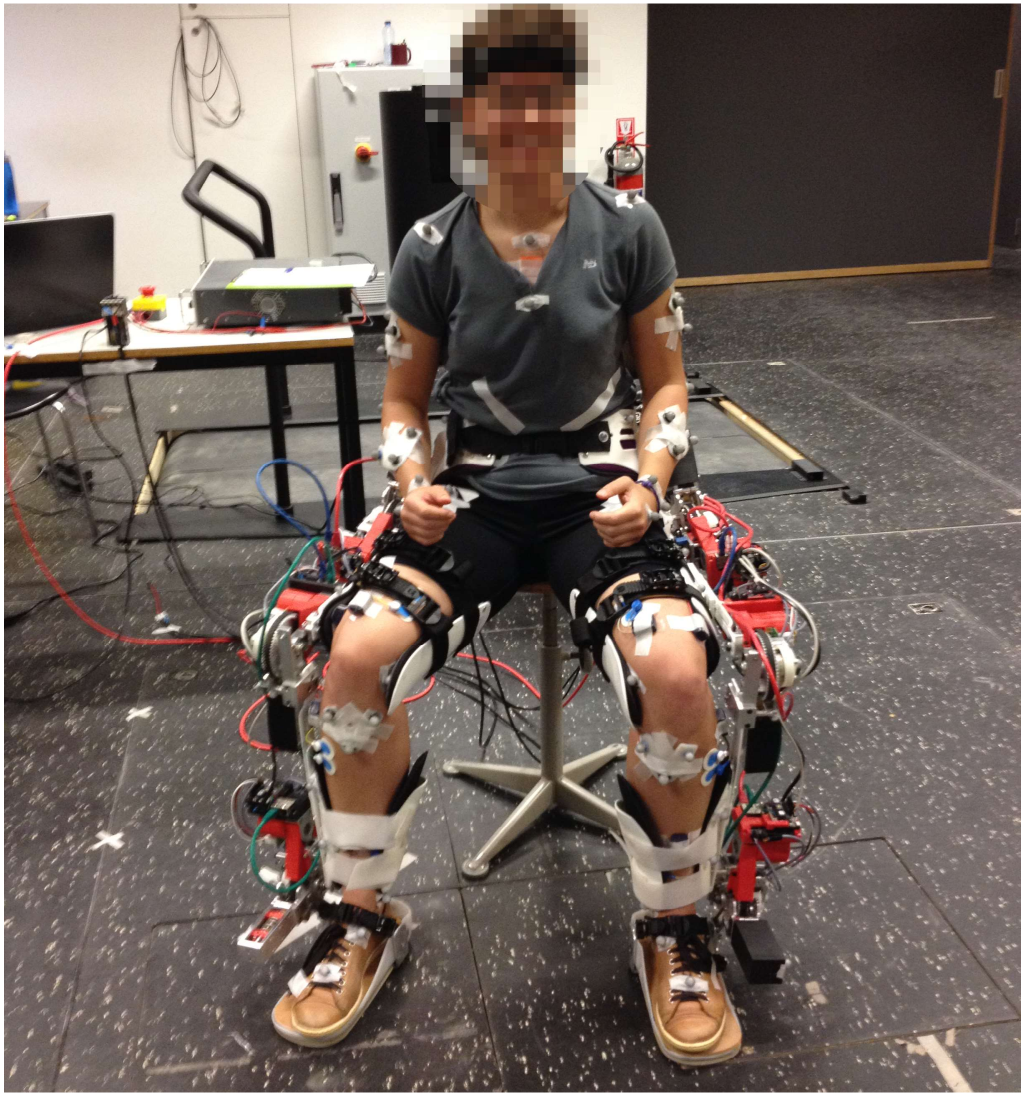
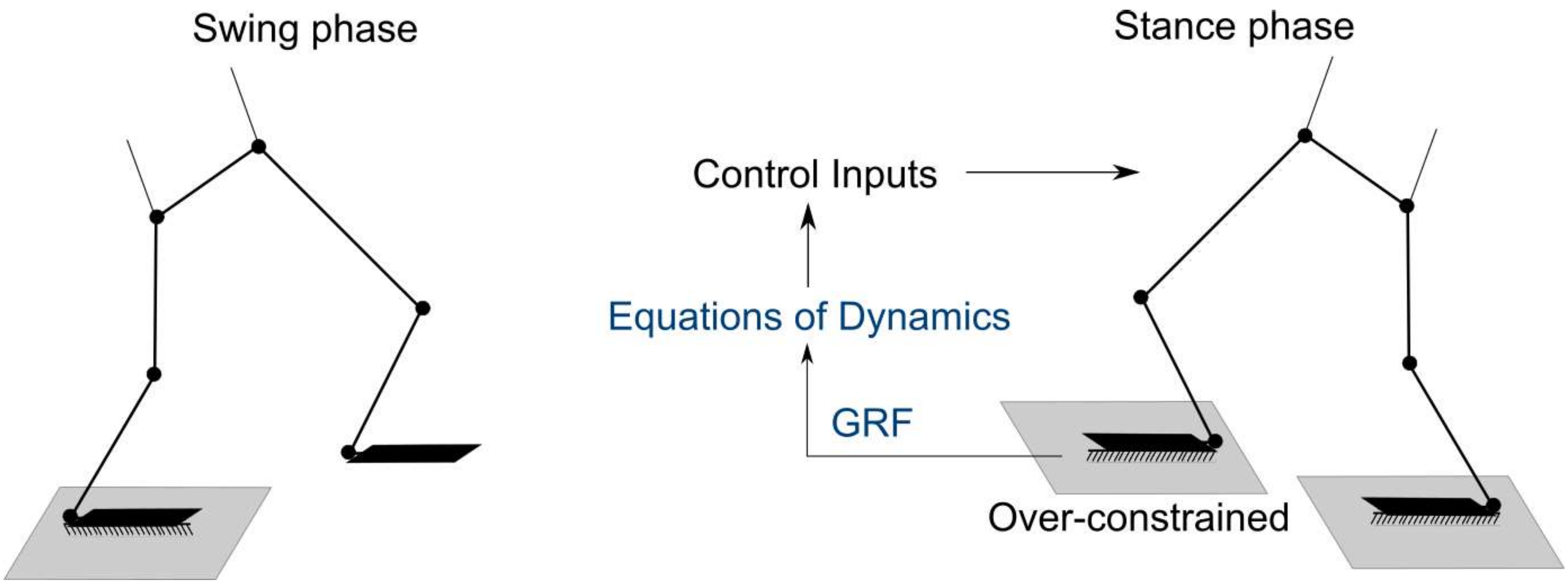
Introduction

Lower limb exoskeleton $\Rightarrow$ mobility assistance/ rehabilitation



Introduction



- Method proposed to obtain physically inspired solution
- Applied on stand-alone exoskeleton $\Rightarrow$ similar to humanoids and other legged robots

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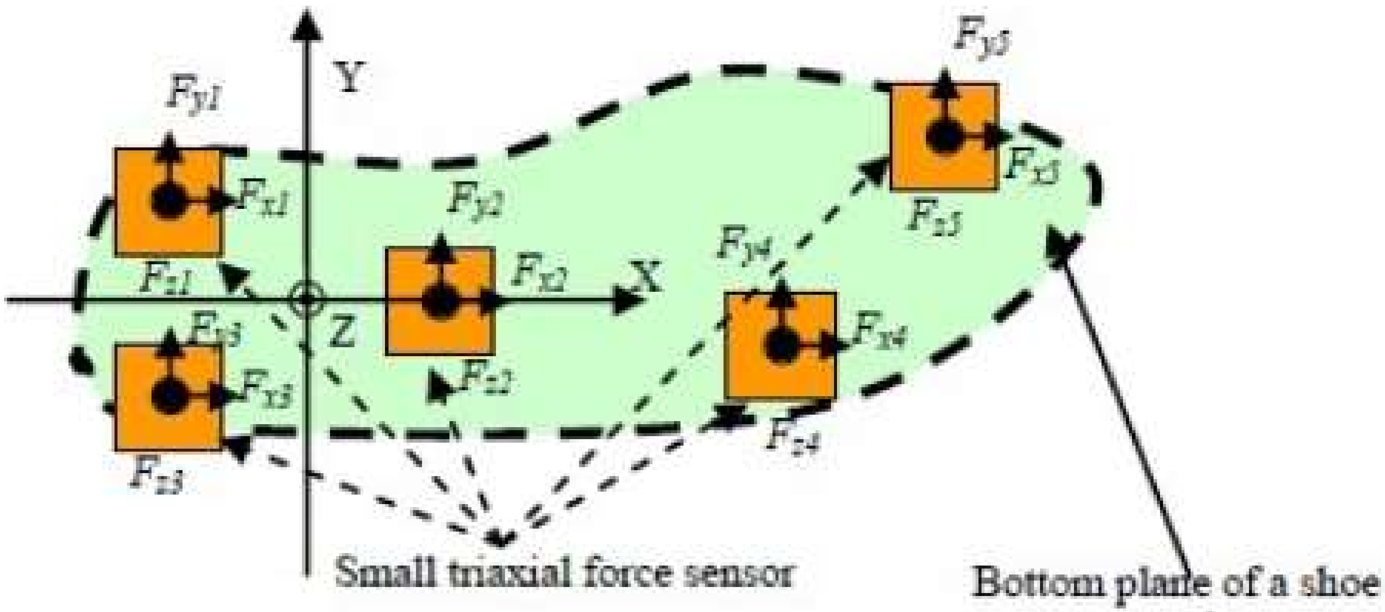
Introduction

Research Background



Measuring the GRFs using force cells [Tao et al., 2012]

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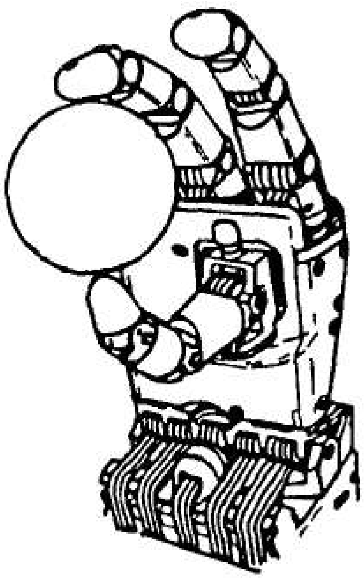
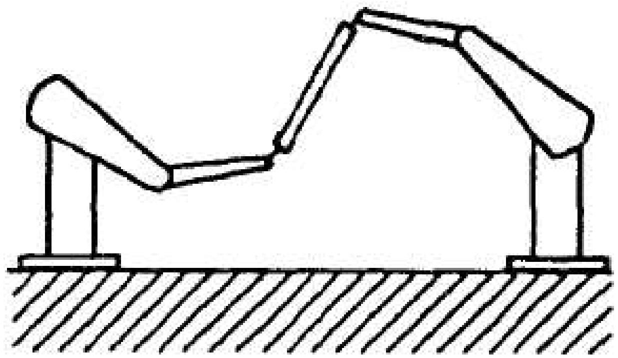
Introduction

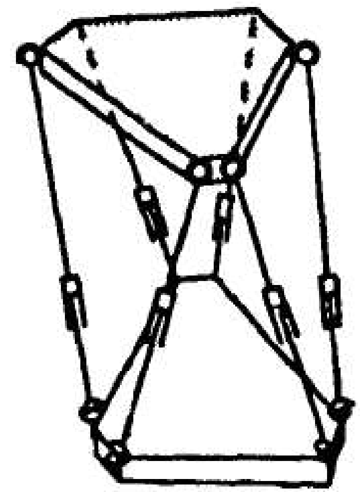
Research Background



Grasping



Cooperative Robots



Parallel Manipulator

[Nahon, 1993]

Estimating the GRFs using the optimization techniques

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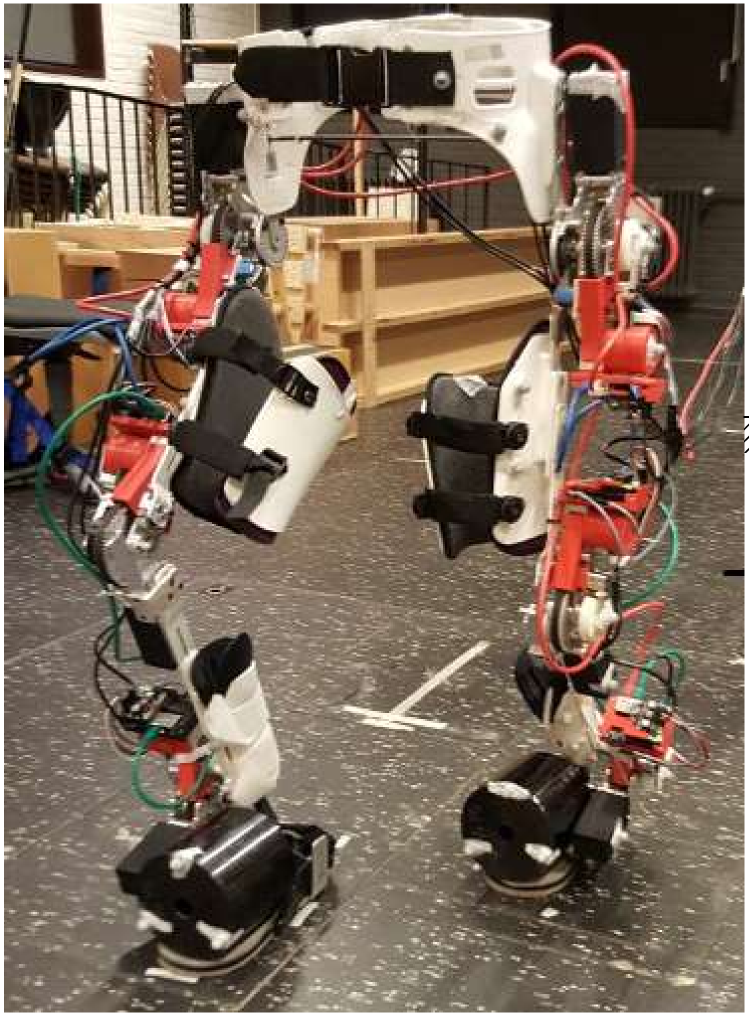
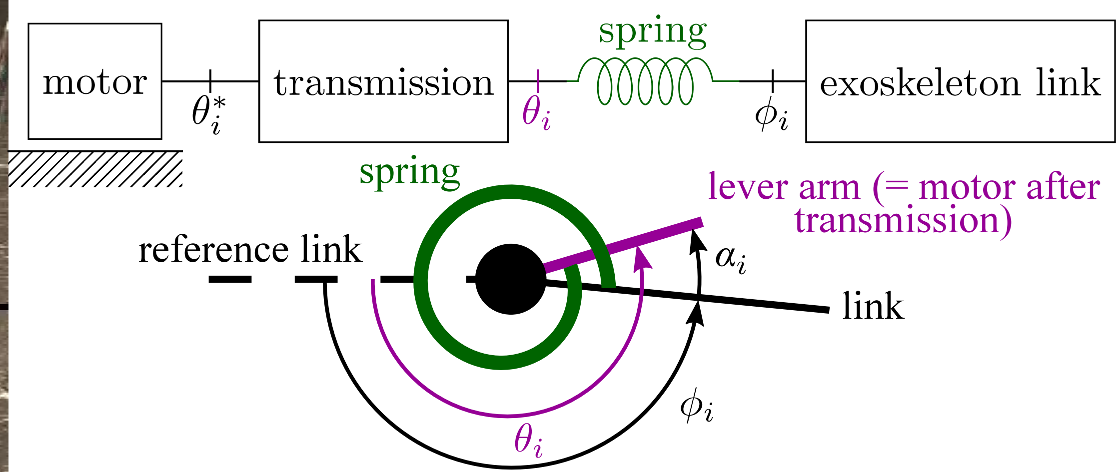
Exoskeleton

Design



MIRAD Exoskeleton



Serial Elastic Actuator

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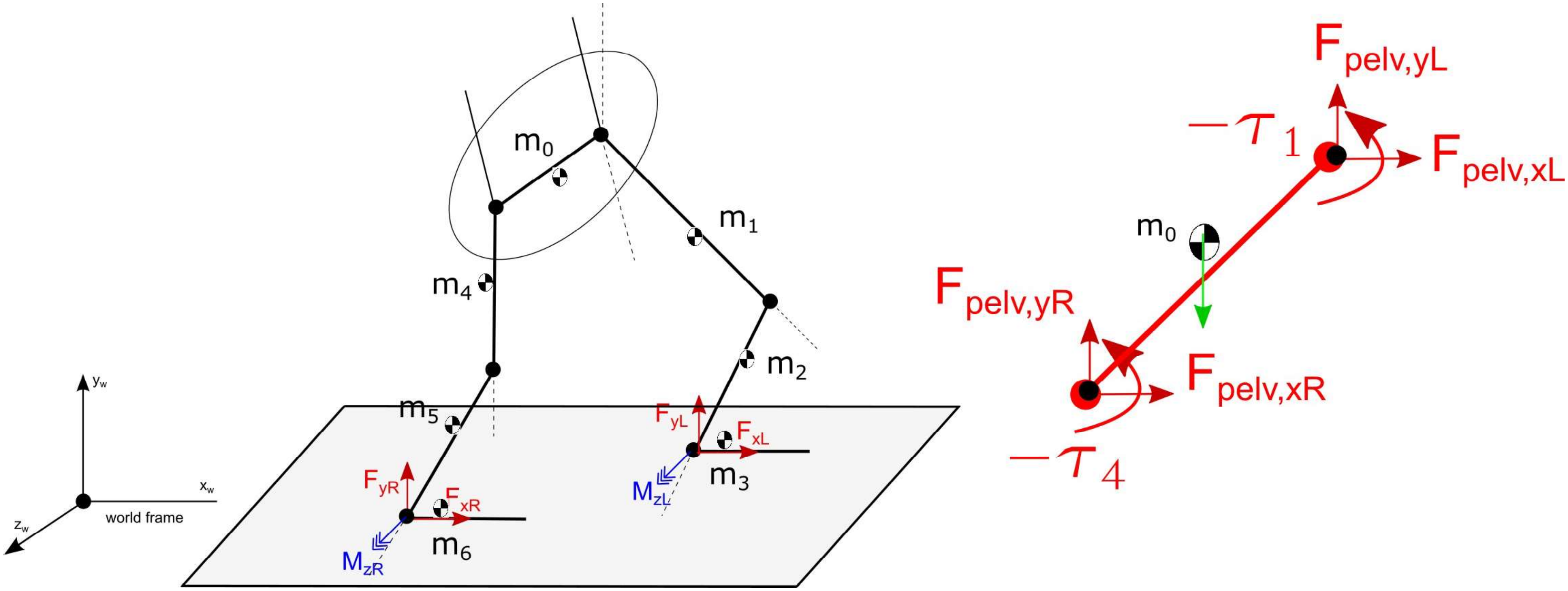
Exoskeleton

Stiffness Model

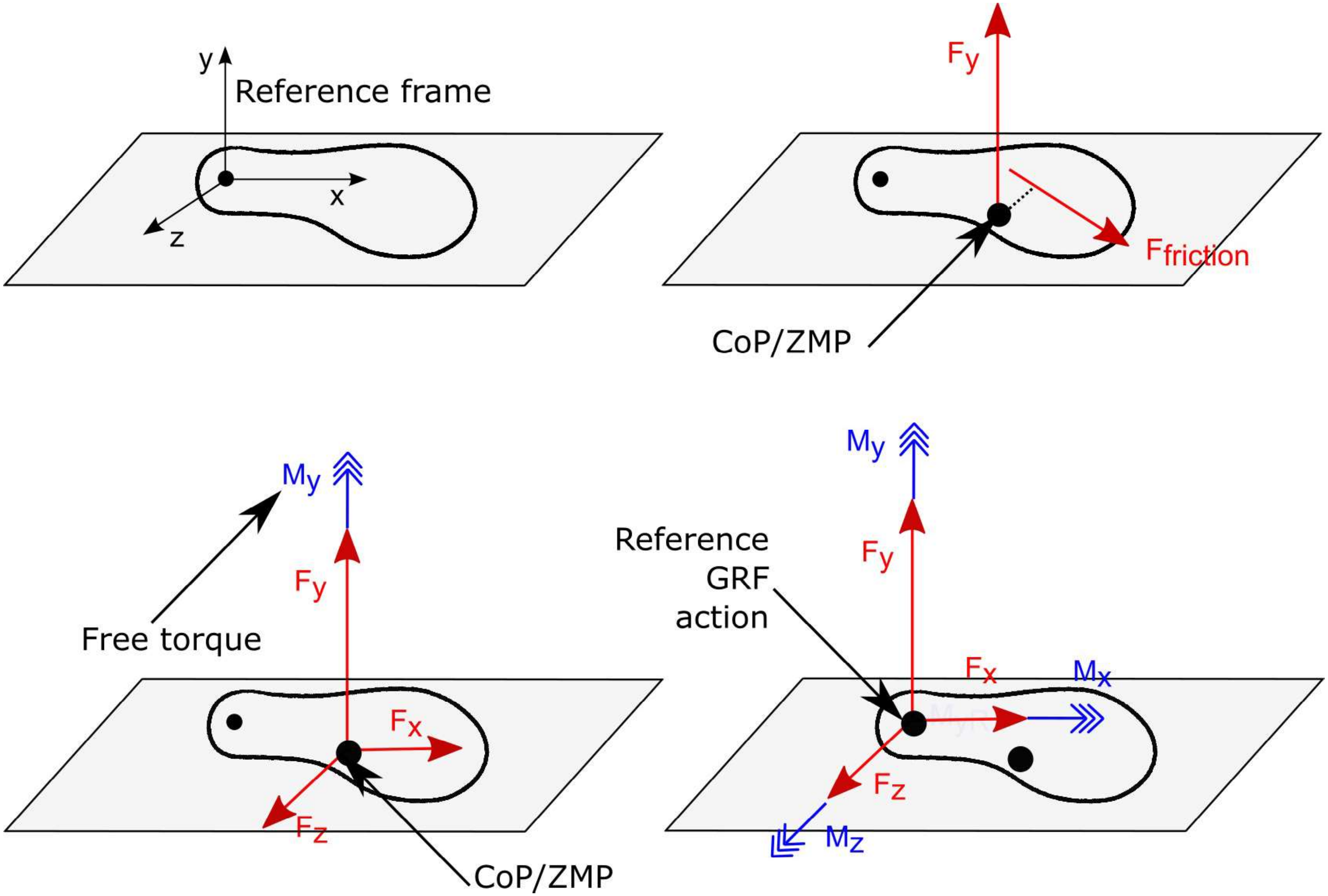


Compliances in the system

- Joint actuators
- Pelvis joining the two legs
- Links are many times stiffer (neglected)

Exoskeleton

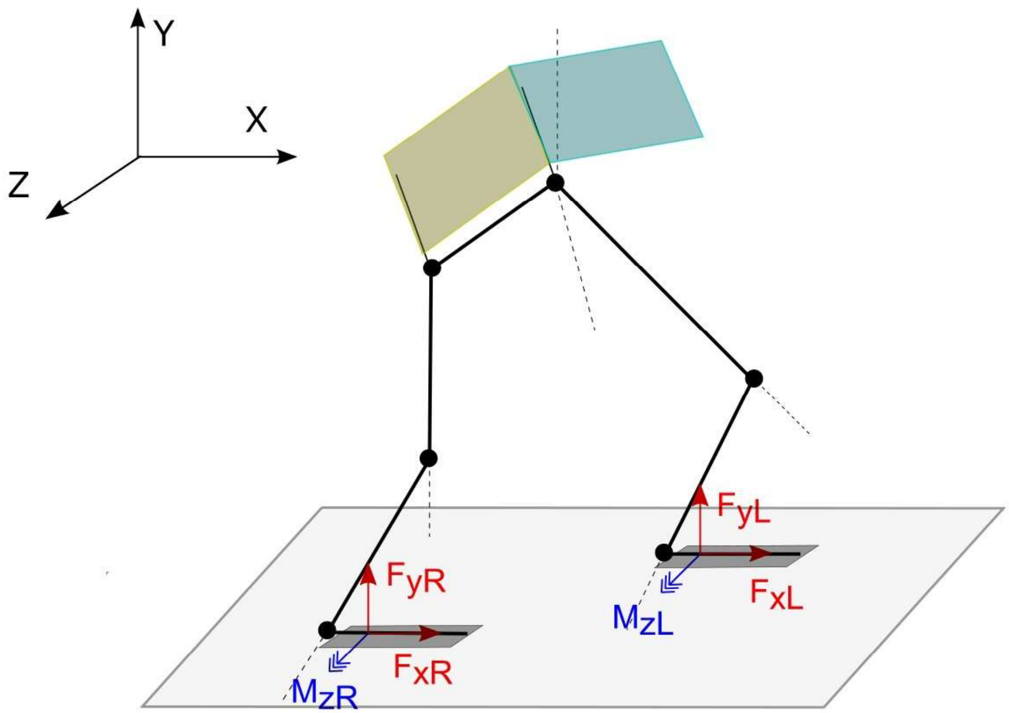
GRF model at a foot



Exoskeleton

Dynamic Model

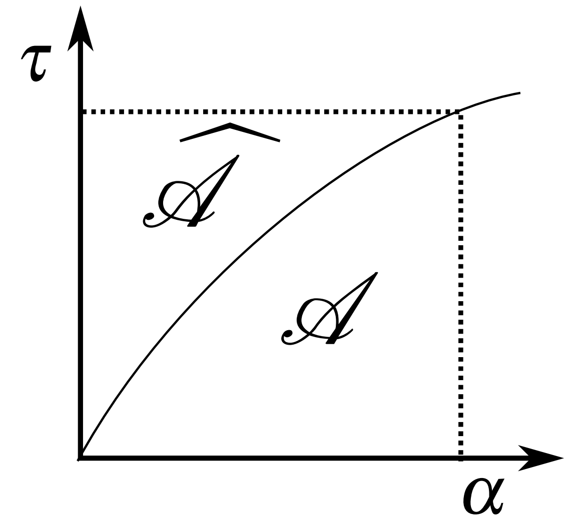
$$\boldsymbol{M}(\boldsymbol{q})\,\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\,\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{S}^T\,\boldsymbol{\tau}_{spr} + \boldsymbol{J}_c(\boldsymbol{q})^T\,\boldsymbol{w}_c$$



Solution Strategy

Complementary Energy Methods

- Equations of compatibility can be derived from the generalized force approaches which work on a scalar quantity called complementary energy



Torque versus deflection curve

- Corollary of the principle of minimum complementary energy: Castigliano's theorem, Crotti-Engesser theorem

$$\widehat{\mathscr{A}} = \sum_{i=1}^{n} \int_0^{\tau_i} \alpha_i(\tau_i)\, d\tau_i$$

$$\frac{\partial \widehat{\mathscr{A}}}{\partial w_j} = \sum_{i=1}^{n} \alpha_i(\tau_i) \frac{\partial \tau_i}{\partial w_j} = 0$$

Solution Strategy

Applied to the exoskeleton

- Equilibrium Equations

$$\boldsymbol{M}_{flb}\,\ddot{\boldsymbol{q}} + \boldsymbol{C}_{flb}\,\dot{\boldsymbol{q}} + \boldsymbol{g}_{flb} = \boldsymbol{J}_{Lf,flb}^{T}\;\boldsymbol{w_L} + \boldsymbol{J}_{Rf,flb}^{T}\;\boldsymbol{w_R}$$

$$\boldsymbol{M_L}\,\ddot{\boldsymbol{q}} + \boldsymbol{C_L}\,\dot{\boldsymbol{q}} + \boldsymbol{g_L} = \boldsymbol{\tau}_{spr,L} + \boldsymbol{J}_{Lf,L}^{T}\;\boldsymbol{w_L}$$

$$\boldsymbol{M_R}\,\ddot{\boldsymbol{q}} + \boldsymbol{C_R}\,\dot{\boldsymbol{q}} + \boldsymbol{g_R} = \boldsymbol{\tau}_{spr,R} + \boldsymbol{J}_{Rf,R}^{T}\;\boldsymbol{w_R}$$

- Compatibility Equations

$$((-\boldsymbol{J}_{Lf,L}^{T})\,(\boldsymbol{J}_{Lf,flb}^{T})^{-1}\,(-\boldsymbol{J}_{Rf,flb}^{T}))^{T}\,\boldsymbol{\alpha_L} + (-\boldsymbol{J}_{Rf,R}^{T})^{T}\,\boldsymbol{\alpha_R} + [..] = 0_{3\times 1}$$

- Constitutive Laws

$$\tau_i = k_{0,i} + k_{1,i}\,\alpha_i + k_{2,i}\,{\alpha_i}^2 + k_{3,i}\,{\alpha_i}^3\,,\ \text{for i} = 1{:}6$$

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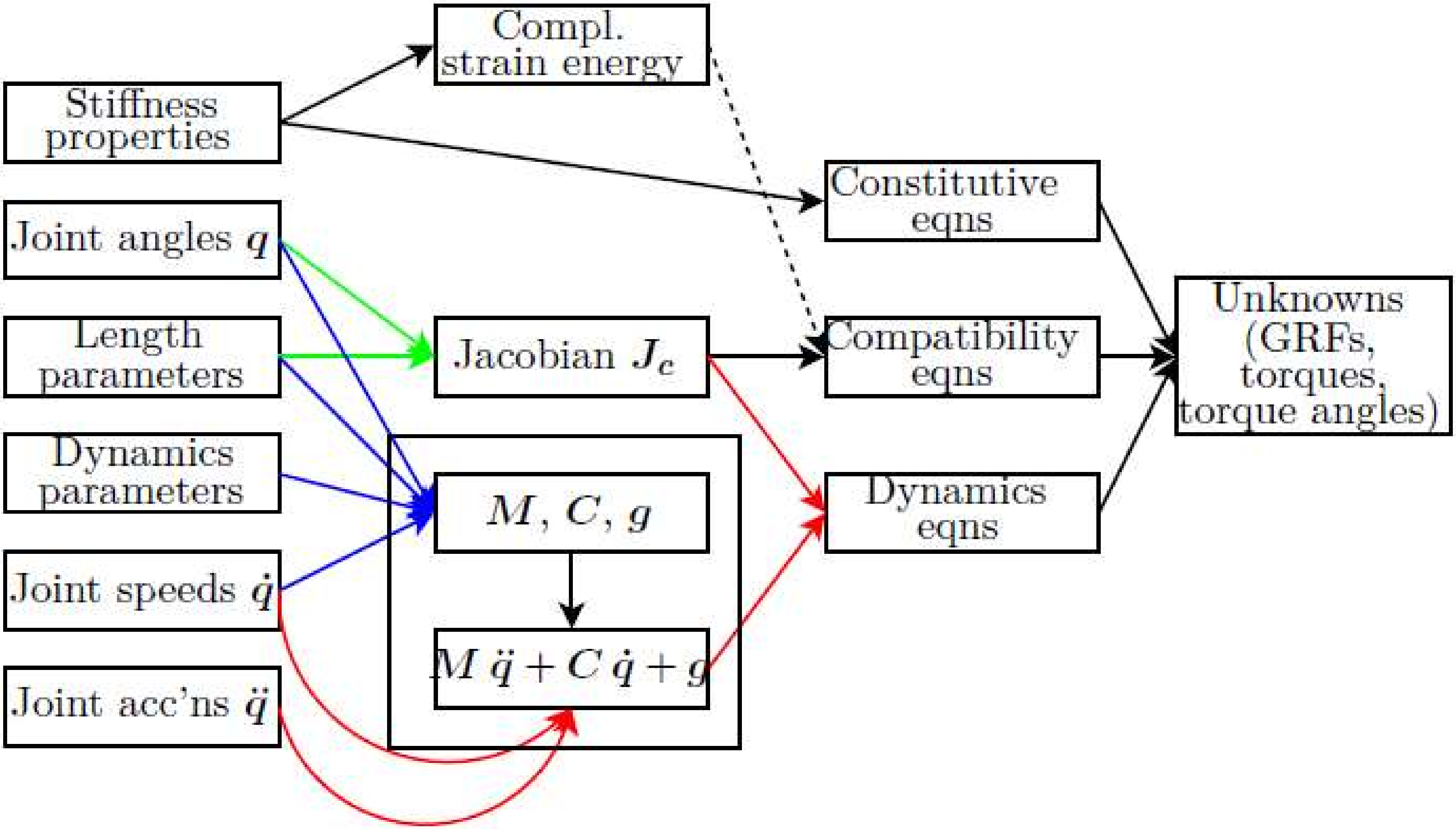
Solution Strategy

Estimation Algorithm



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Solution Strategy

Optimization Formulation

$$\min_{\boldsymbol{w_L}, \boldsymbol{w_R}, \boldsymbol{\tau}_{spr,L}, \boldsymbol{\tau}_{spr,R} \boldsymbol{\alpha}} \quad \sum_{i=1}^{6} \left(\int_0^{\tau_i} \alpha_i \, d\tau_i \right) + \frac{1}{2K_{pelv,x}} (2F_{x,R} - \overline{\tau_{dyn,flb,x}})^2 + \frac{1}{2K_{pelv,x}} (2F_{y,R} - \overline{\tau_{dyn,flb,y}})^2$$

subject to

$$\boldsymbol{M}_{flb} \, \ddot{\boldsymbol{q}} + \boldsymbol{C}_{flb} \, \dot{\boldsymbol{q}} + \boldsymbol{g}_{flb} = \boldsymbol{J}_{Lf,flb}^T \, \boldsymbol{w_L} + \boldsymbol{J}_{Rf,flb}^T \, \boldsymbol{w_R}$$

$$\boldsymbol{M_L} \, \ddot{\boldsymbol{q}} + \boldsymbol{C_L} \, \dot{\boldsymbol{q}} + \boldsymbol{g_L} = \boldsymbol{\tau}_{spr,L} + \boldsymbol{J}_{Lf,L}^T \, \boldsymbol{w_L}$$

$$\boldsymbol{M_R} \, \ddot{\boldsymbol{q}} + \boldsymbol{C_R} \, \dot{\boldsymbol{q}} + \boldsymbol{g_R} = \boldsymbol{\tau}_{spr,R} + \boldsymbol{J}_{Rf,R}^T \, \boldsymbol{w_R}$$

$$\tau_i = k_{0,i} + k_{1,i} \cdot \alpha_i + k_{2,i} \cdot \alpha_i^2 + k_{3,i} \cdot \alpha_i^3 \text{ for i } = 1{:}6 \; .$$

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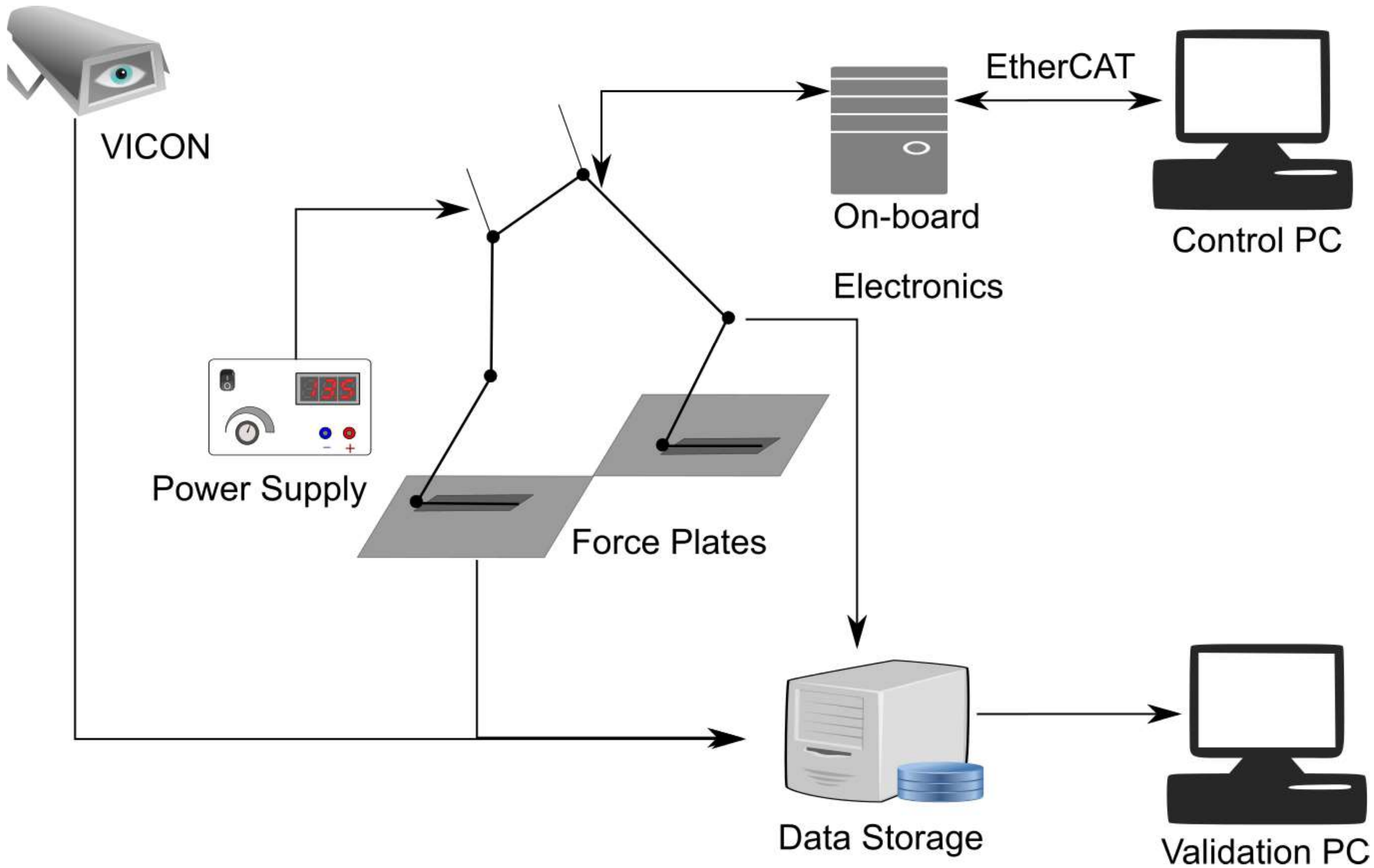
Validation

Set-up



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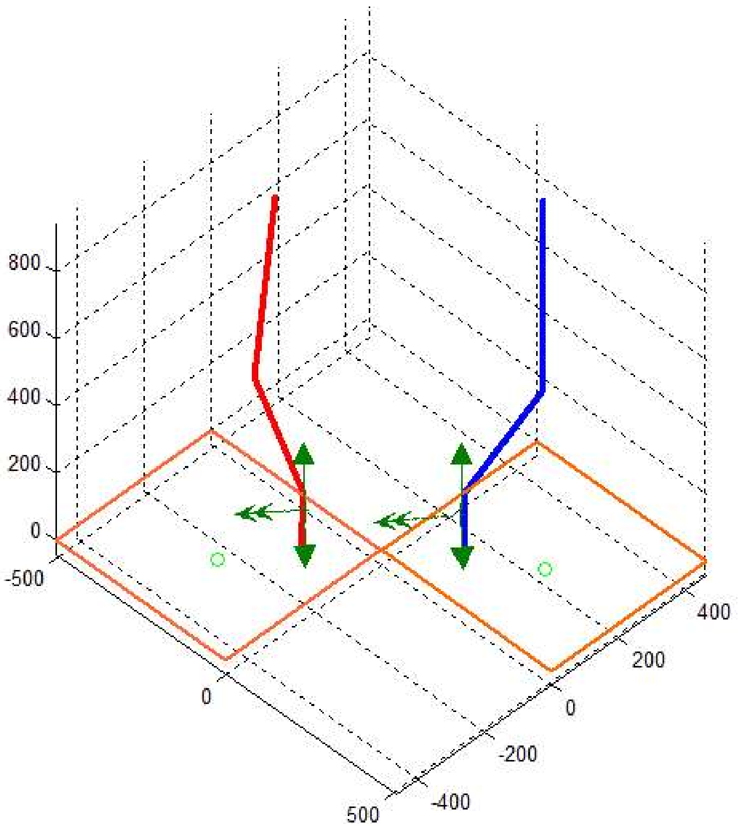
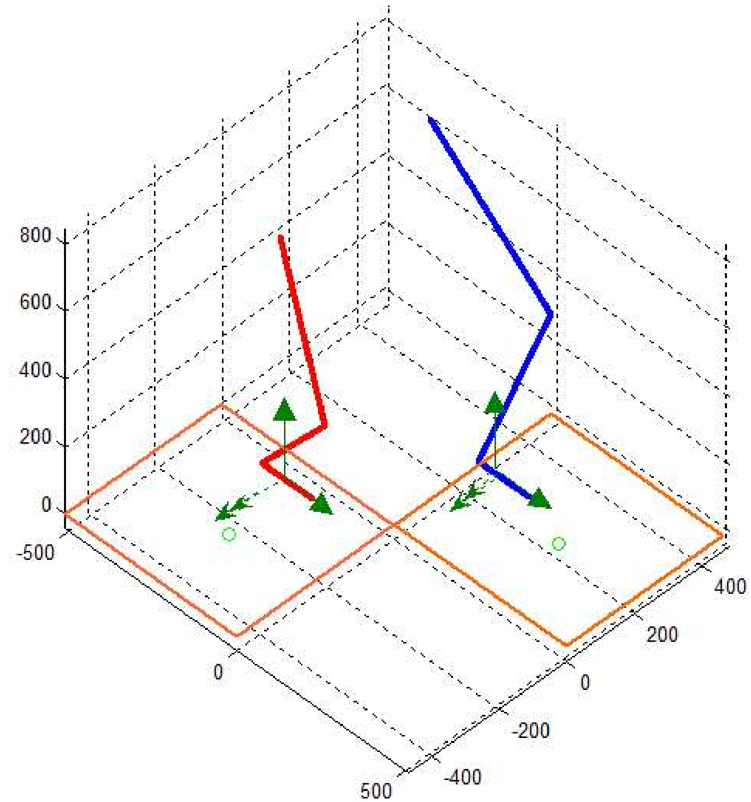
Validation

Procedure



Configuration 1



Configuration 2

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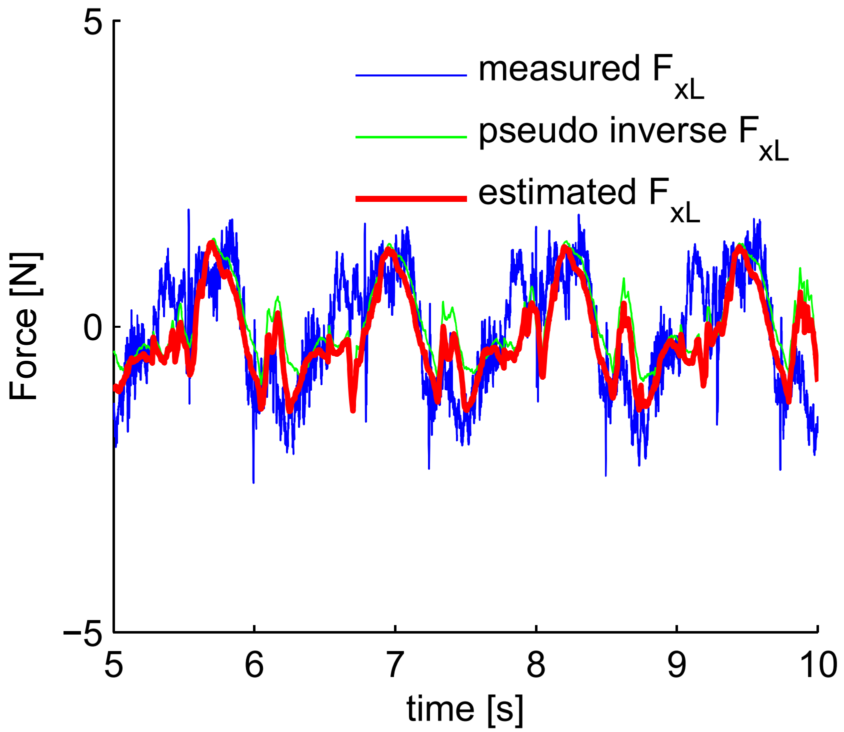
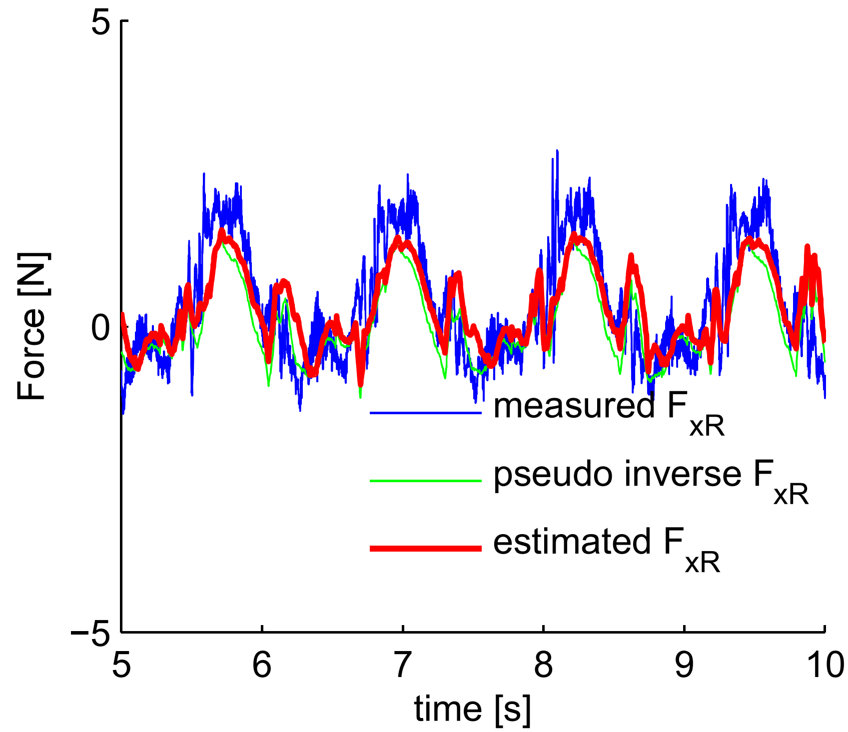
Results: Configuration 1

GRF components F_{xL} and F_{xR}



Horizontal force at left foot F_{xL}



Horizontal force at right foot F_{xR}

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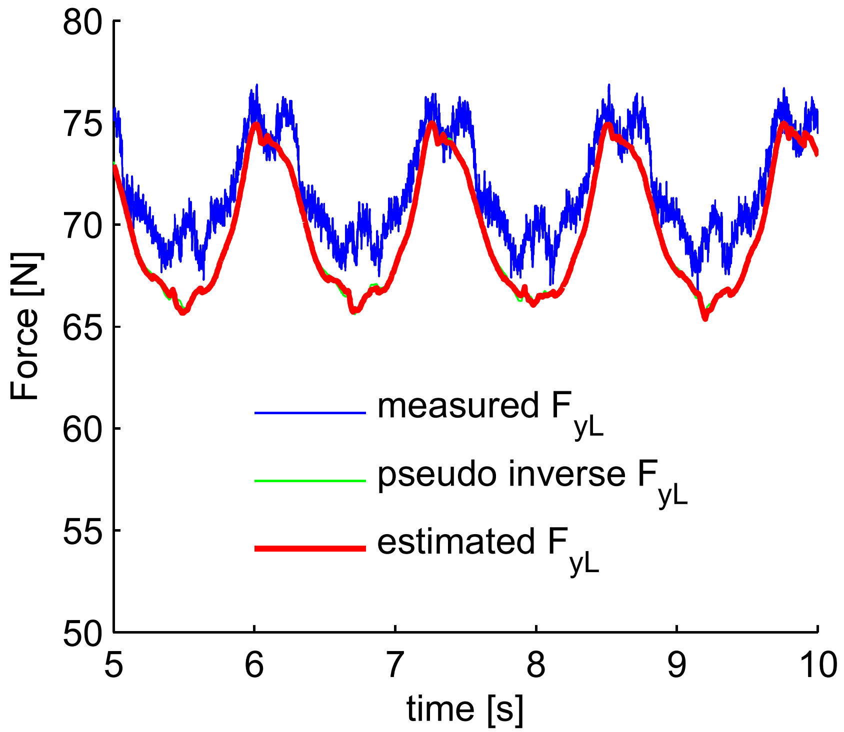
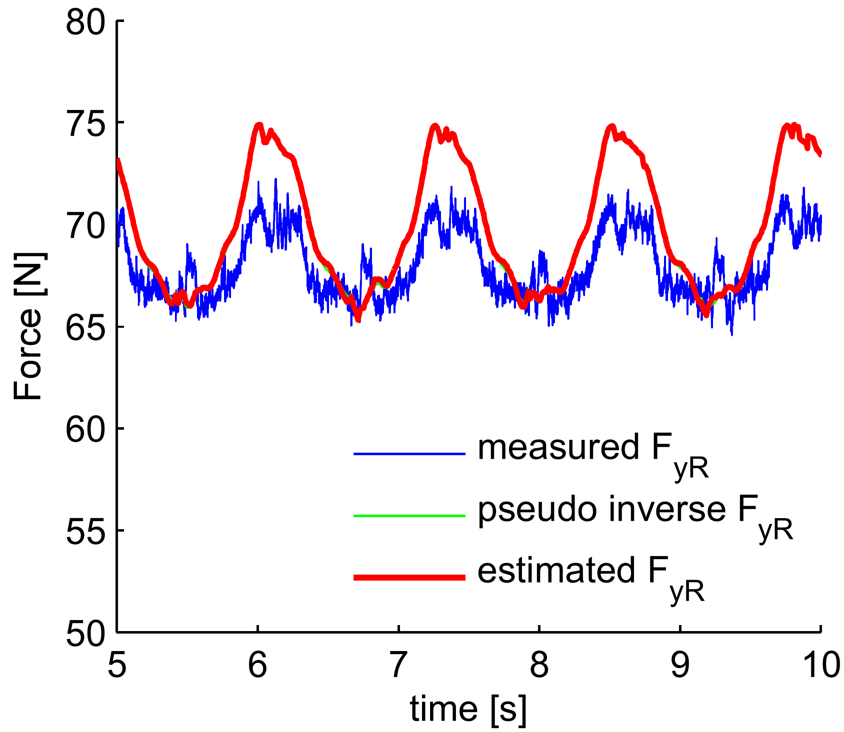
Results: Configuration 1

GRF components F_{yL} and F_{yR}



Vertical force at the left foot F_{yL}



Vertical force at right foot F_{yR}

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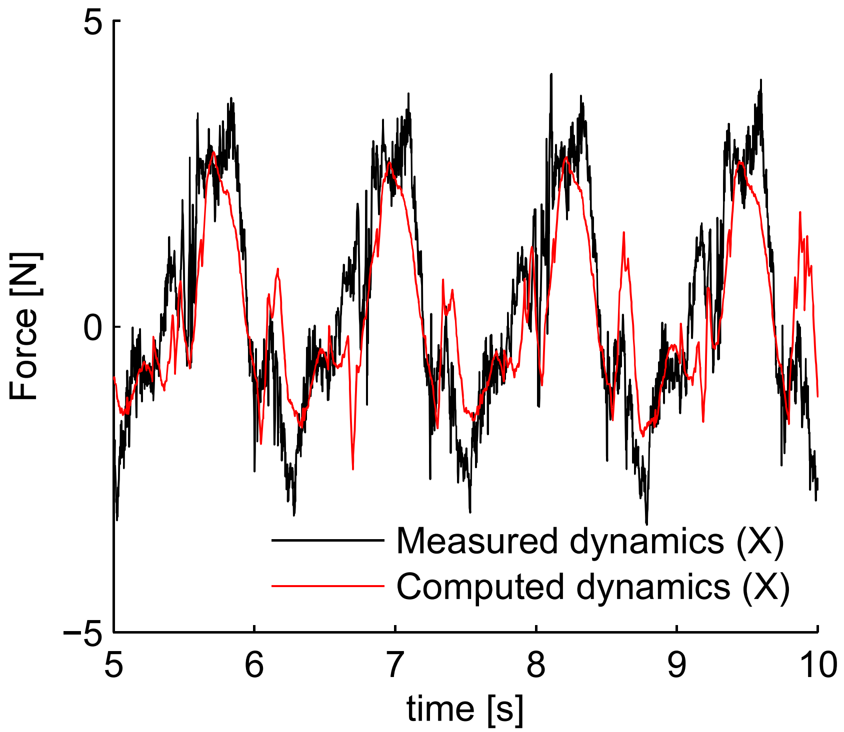
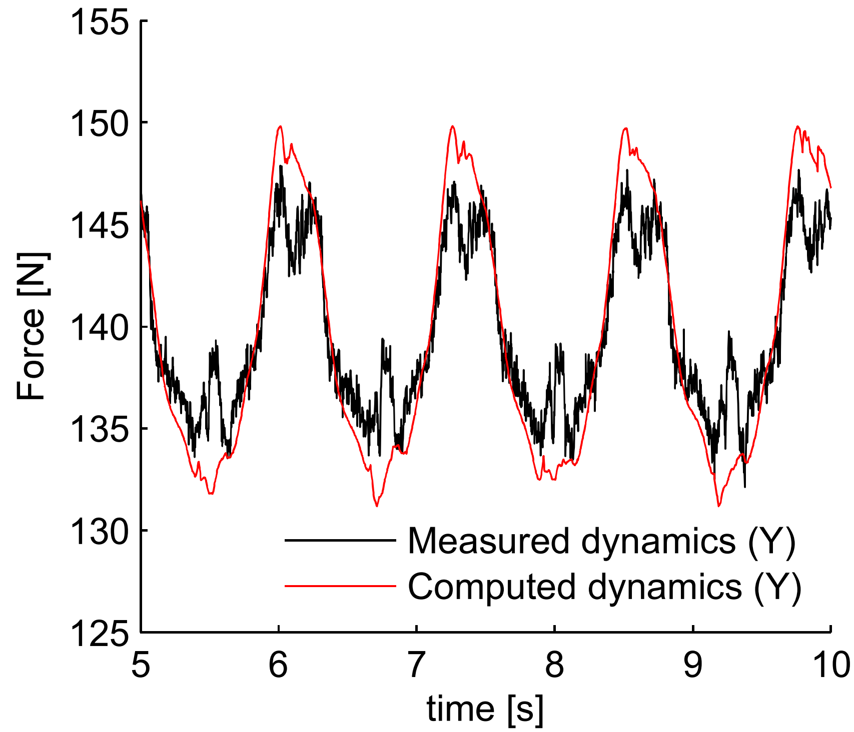
Results: Configuration 1

Analysis of errors in F_{yL} and F_{yR}





- $\boldsymbol{M}_{flb}\ \ddot{\boldsymbol{q}} + \boldsymbol{C}_{flb}\ \dot{\boldsymbol{q}} + \boldsymbol{g}_{flb} = \boldsymbol{\tau}_{dyn,flb} = \boldsymbol{J}^T_{Lf,flb}\ \boldsymbol{w_L} + \boldsymbol{J}^T_{Rf,flb}\ \boldsymbol{w_R}$

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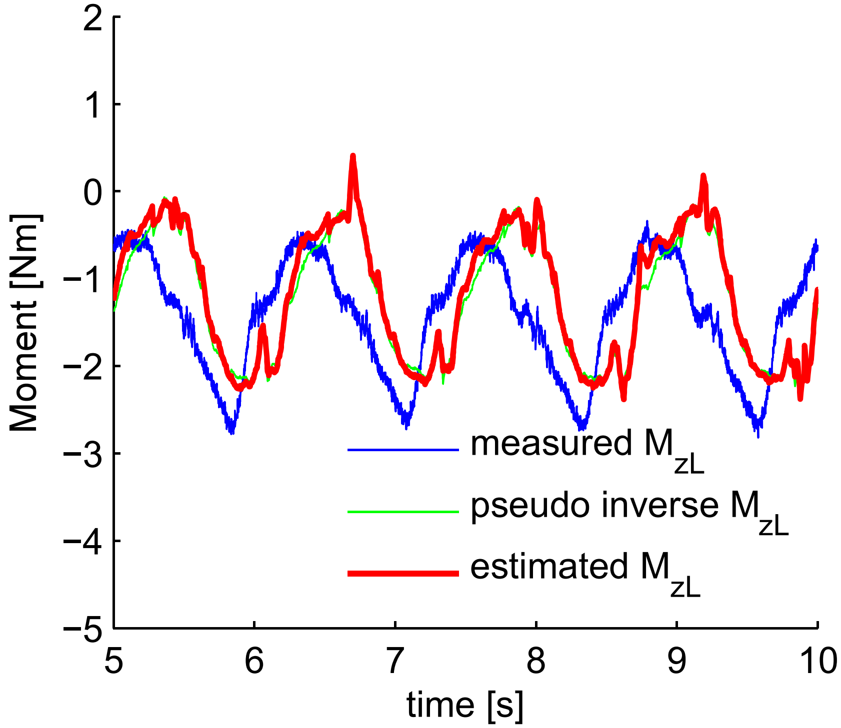
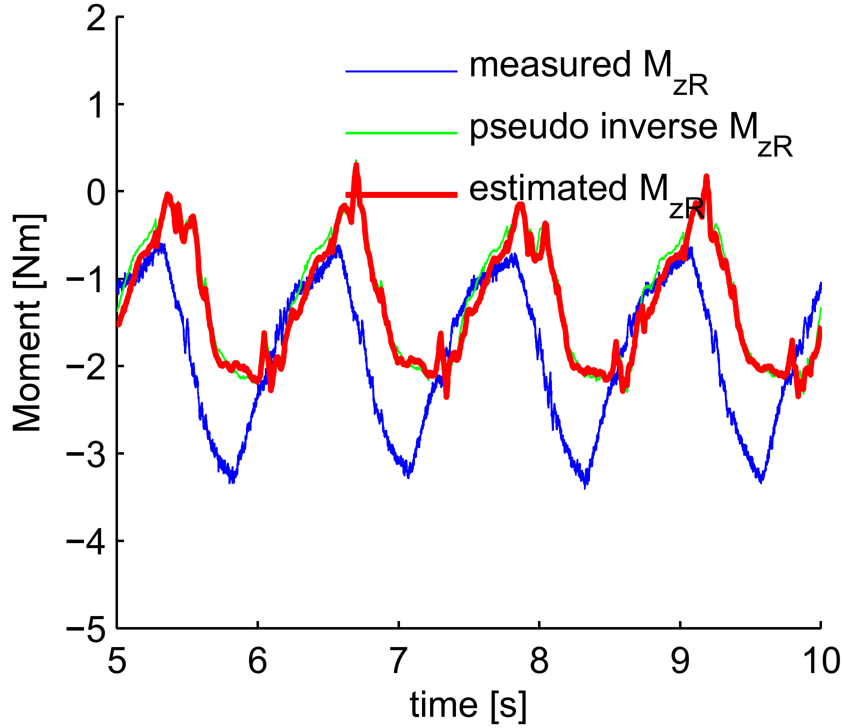
Results: Configuration 1

GRF components M_{zL} and M_{zR}



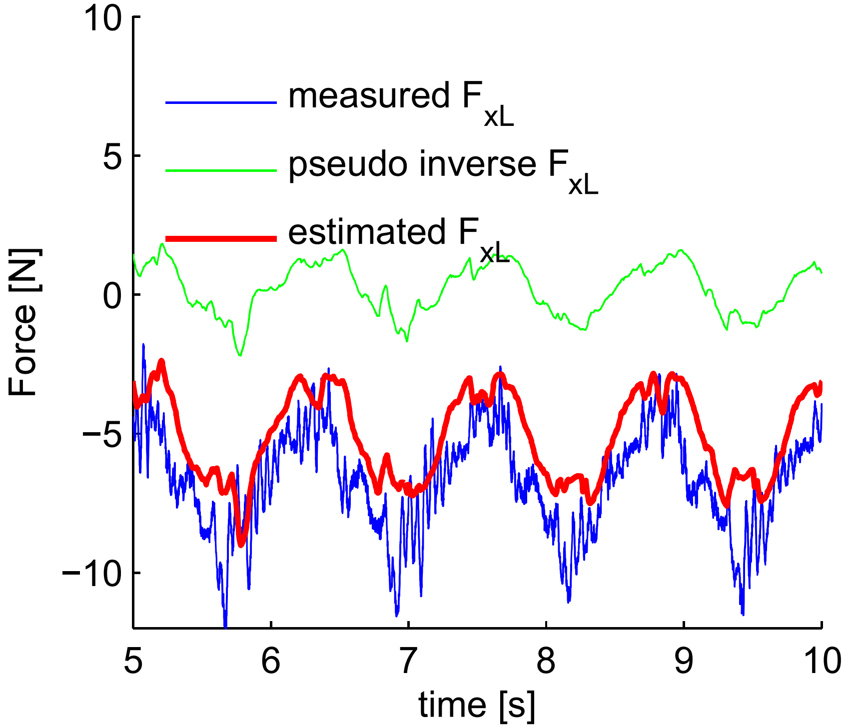
Moment about Z-axis at left foot M_{zL}



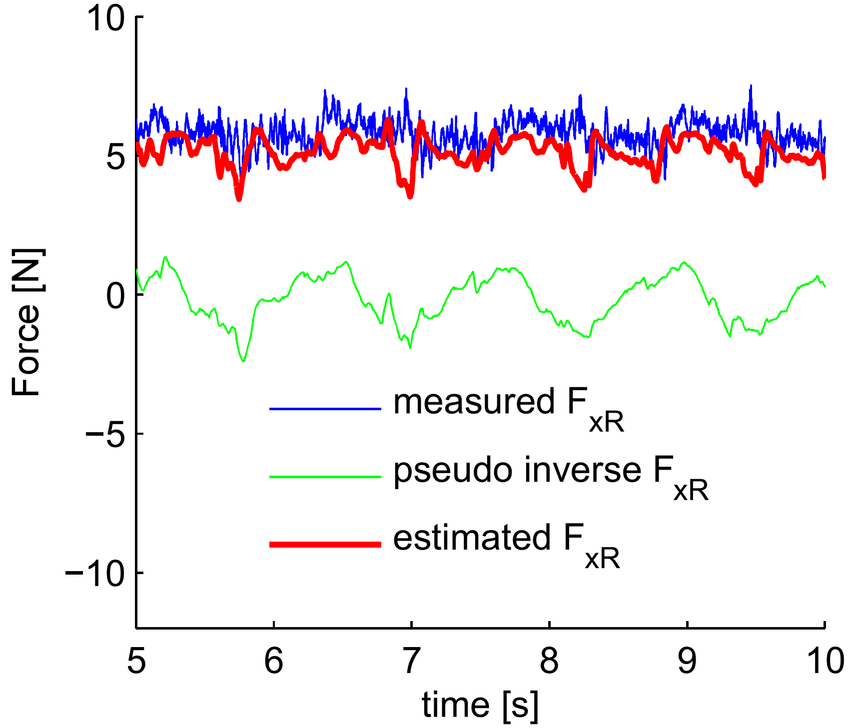
Moment about Z-axis at right foot M_{zR}

Results: Configuration 2

GRF components F_{xL} and F_{xR}



Horizontal force at left foot F_{xL}



Horizontal force at right foot F_{xR}

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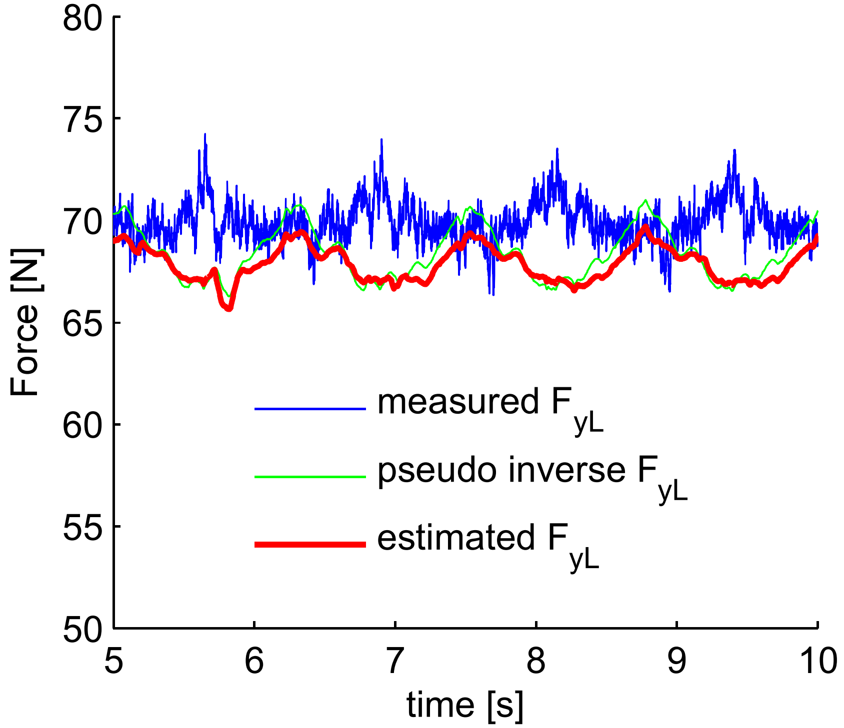
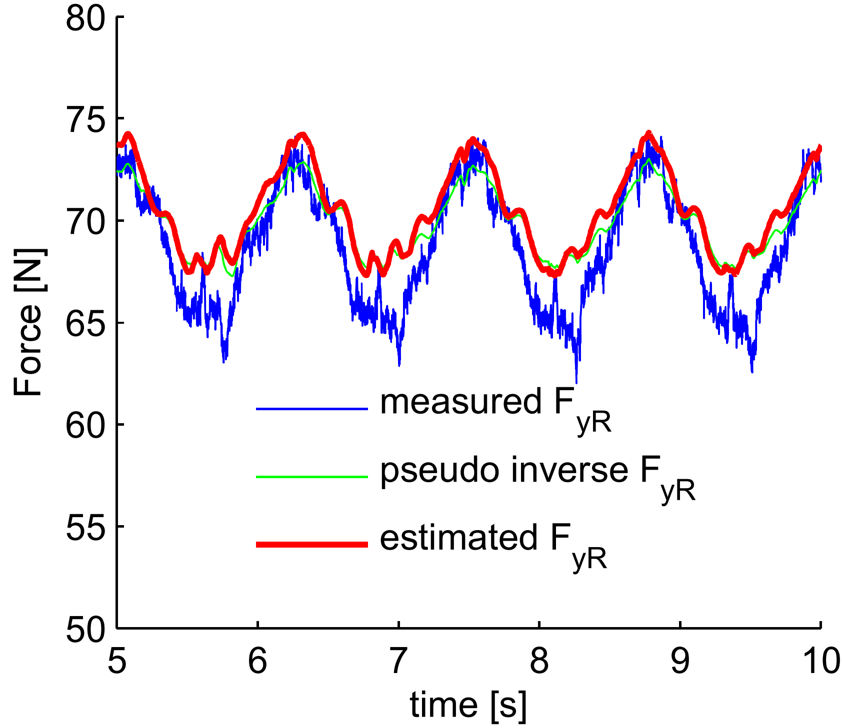
Results: Configuration 2

GRF components F_{yL} and F_{yR}



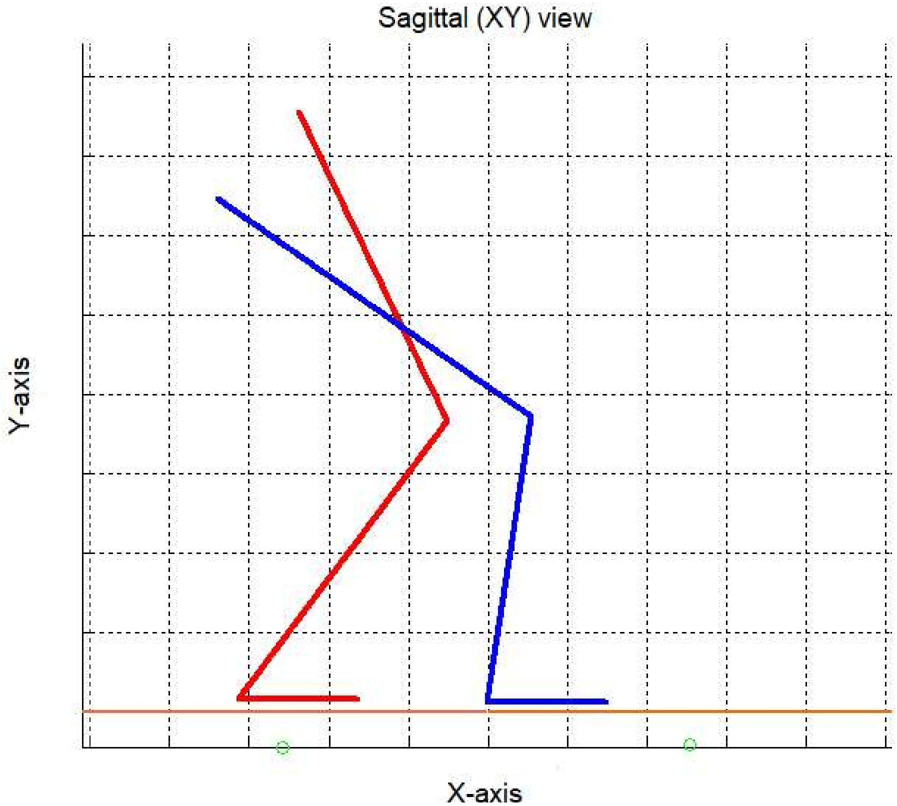
Vertical force at the left foot F_{yL}

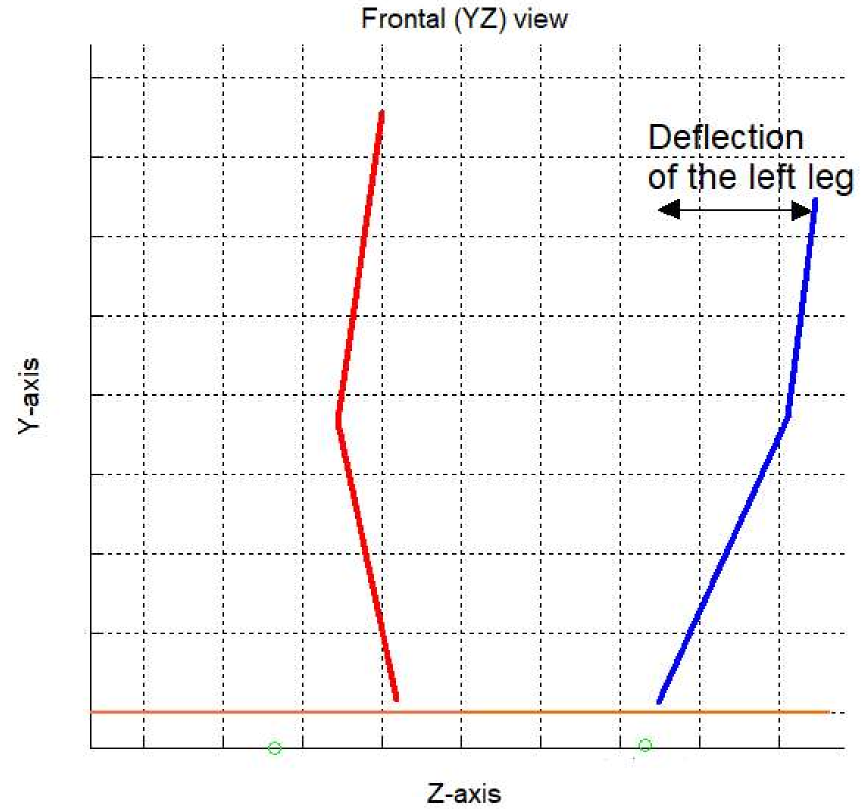


Vertical force at right foot F_{yR}

Results: Configuration 2

Analysis of errors in F_{yL} and F_{yR}





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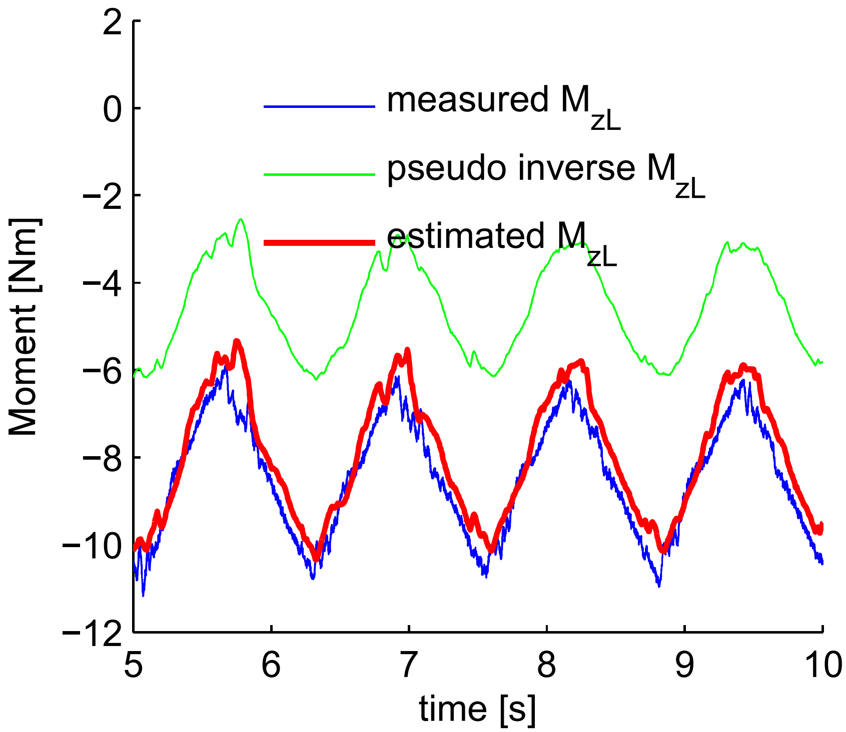
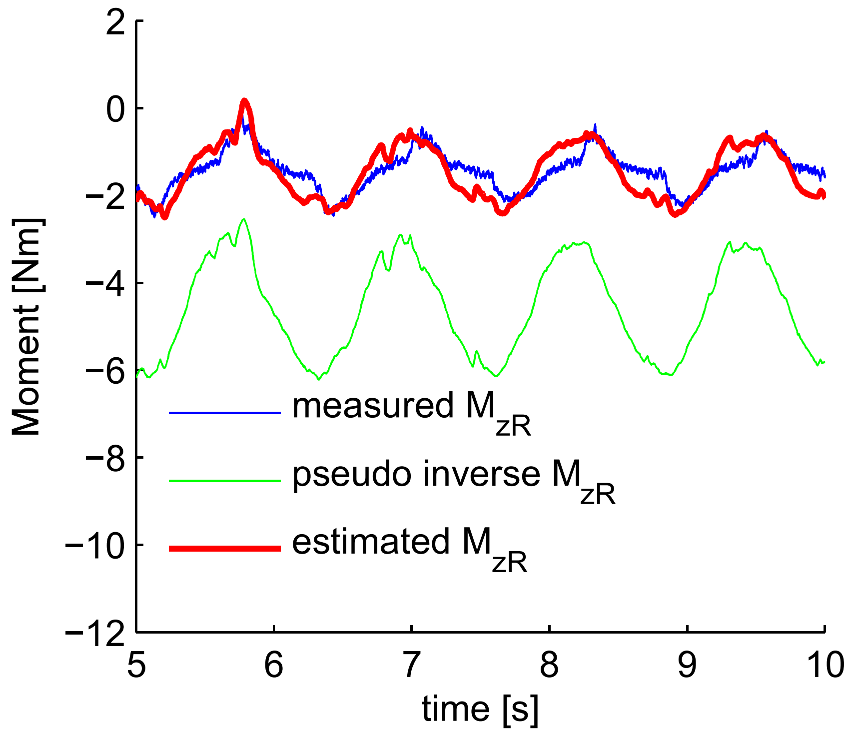
Results: Configuration 2

GRF components M_{zL} and M_{zR}



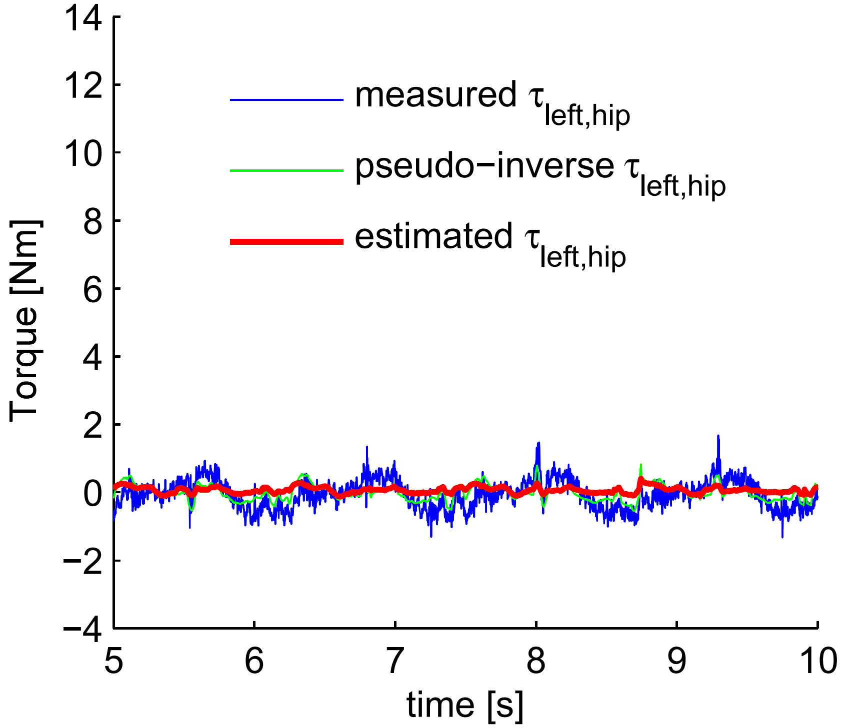
Moment about Z-axis at left foot M_{zL}



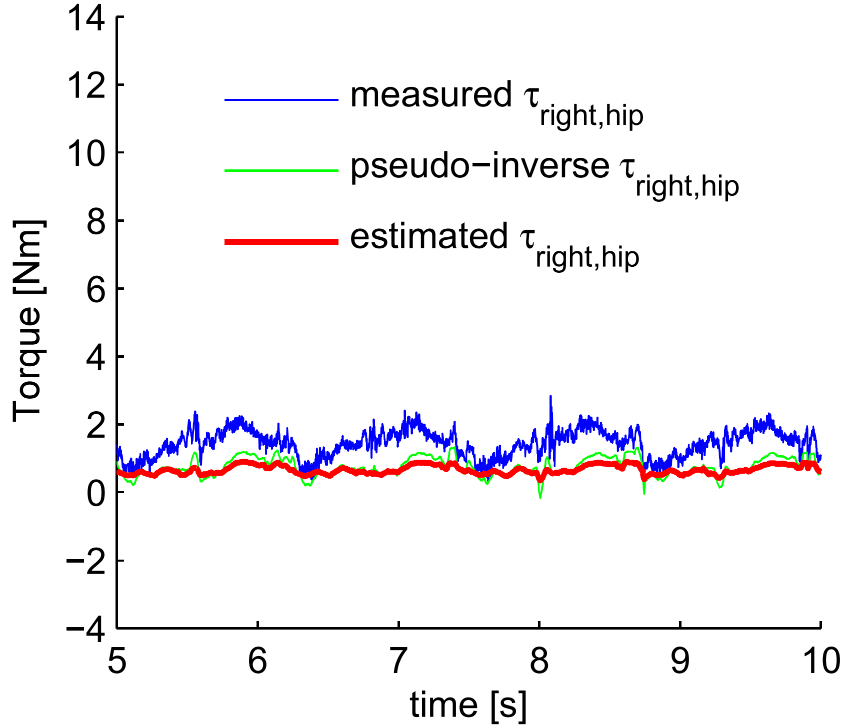
Moment about Z-axis at right foot M_{zR}

Results: Configuration 1

Torques at the hip



Joint torque at left hip $\tau_{L,hip}$



Joint torque at right hip $\tau_{R,hip}$

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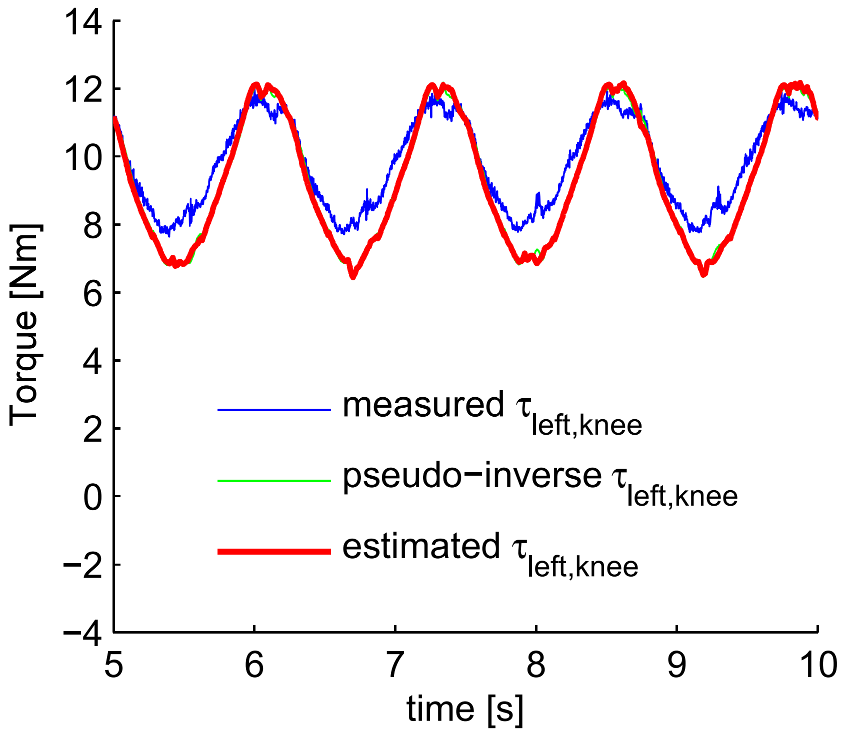
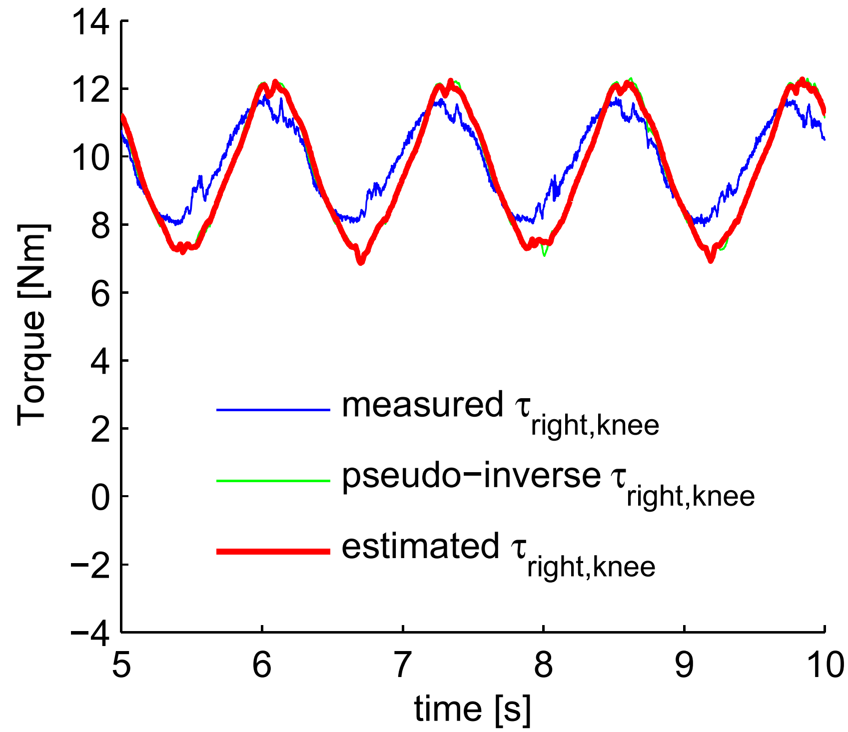
Results: Configuration 1

Torques at the knee



Joint torque at left knee $\tau_{L,knee}$



Joint torque at right knee $\tau_{R,knee}$

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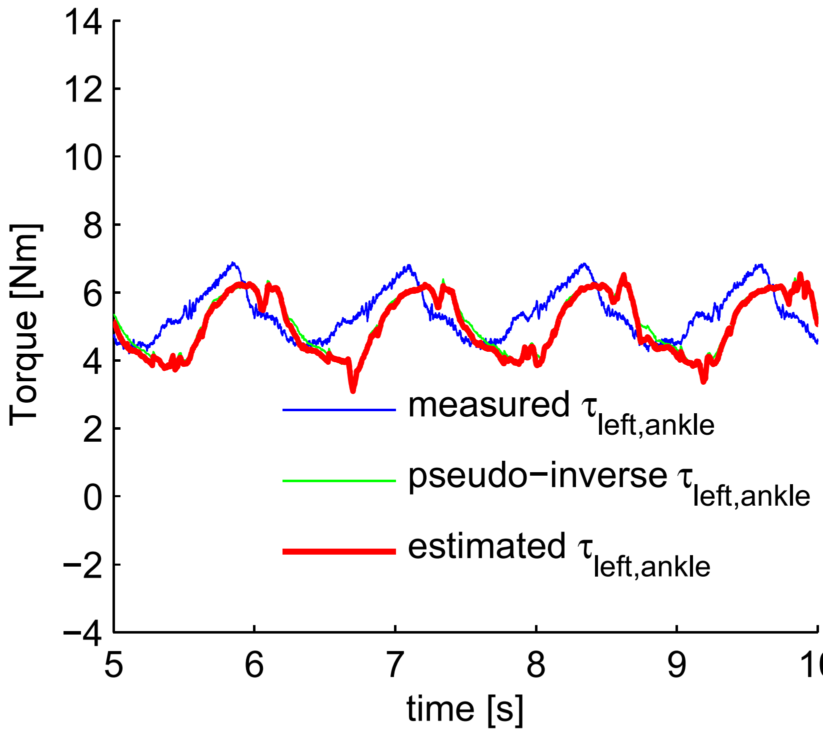
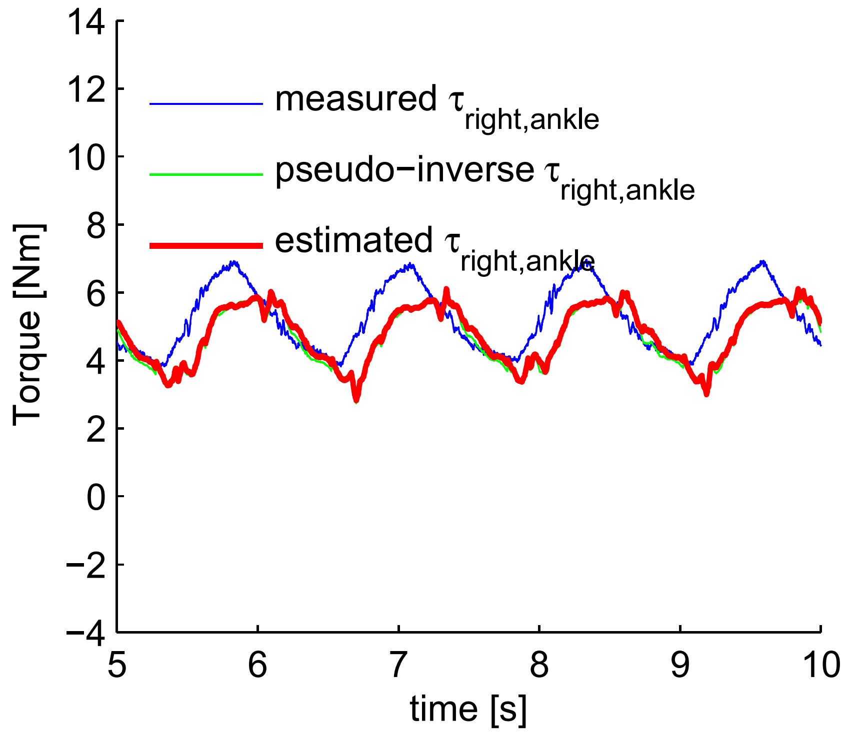
Results: Configuration 1

Torques at the ankle



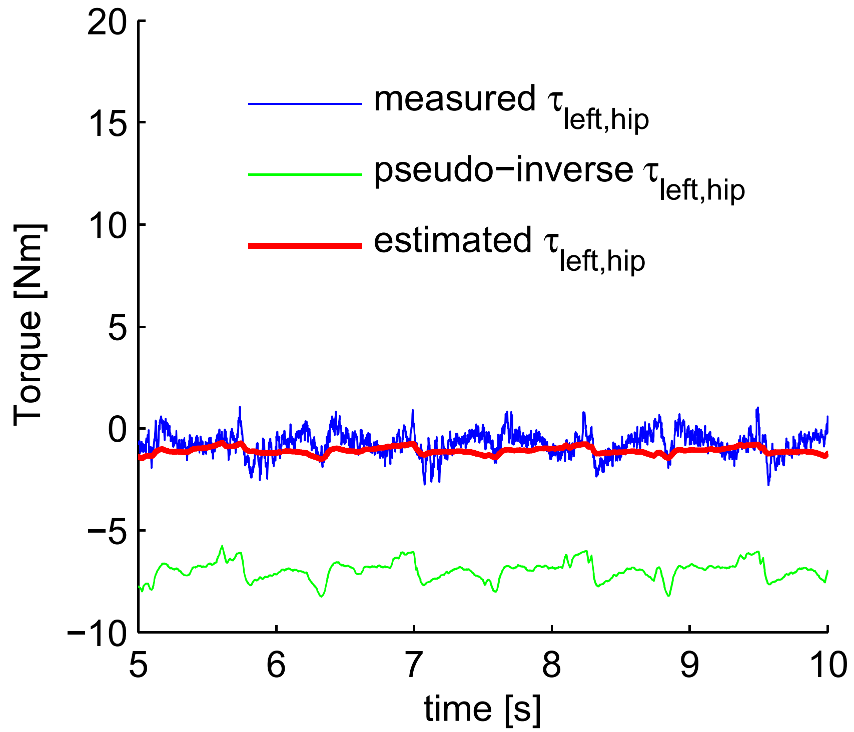
Joint torque at left ankle $\tau_{L,ankle}$



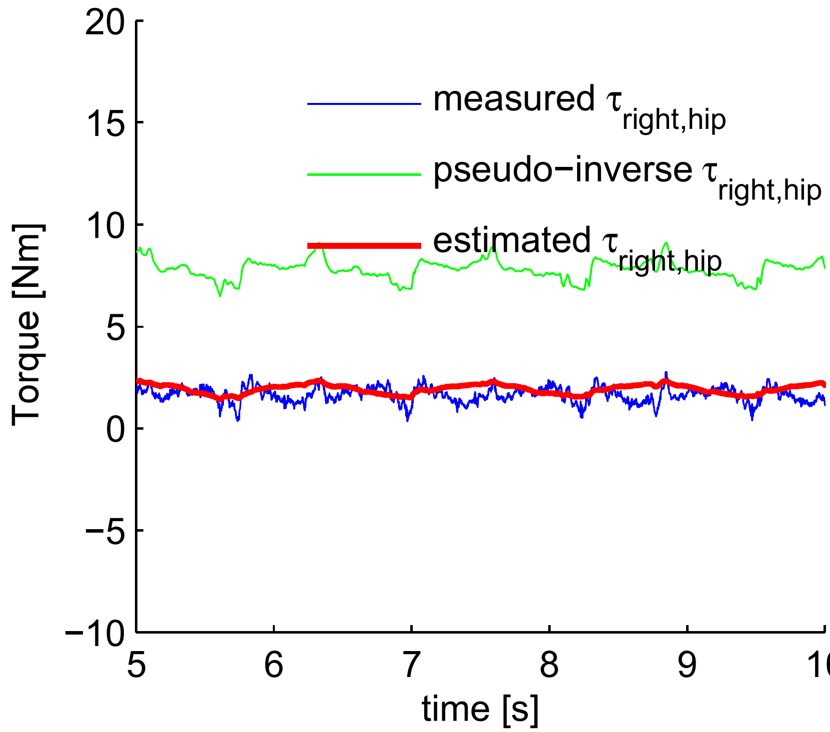
Joint torque at right ankle $\tau_{R,ankle}$

Results: Configuration 2

Torques at the hip



Joint torque at left hip $\tau_{L,hip}$



Joint torque at right hip $\tau_{R,hip}$

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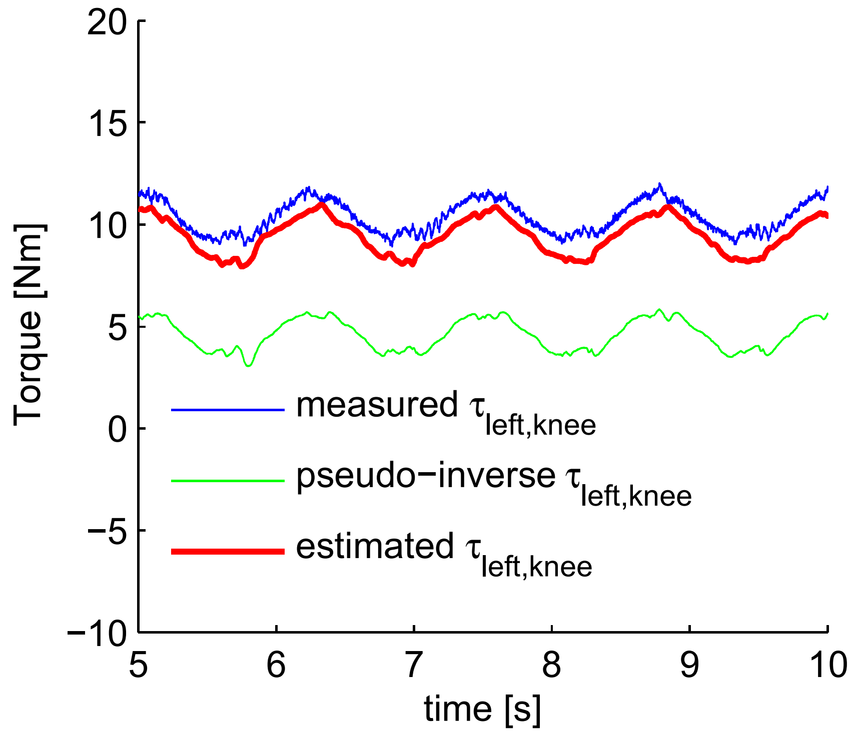
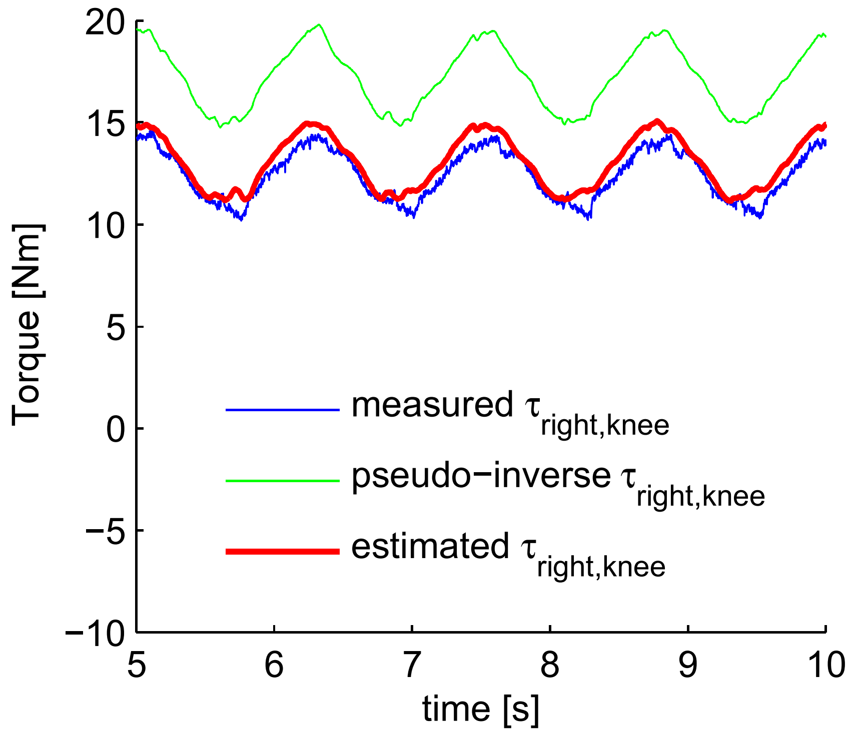
Results: Configuration 2

Torques at the knee



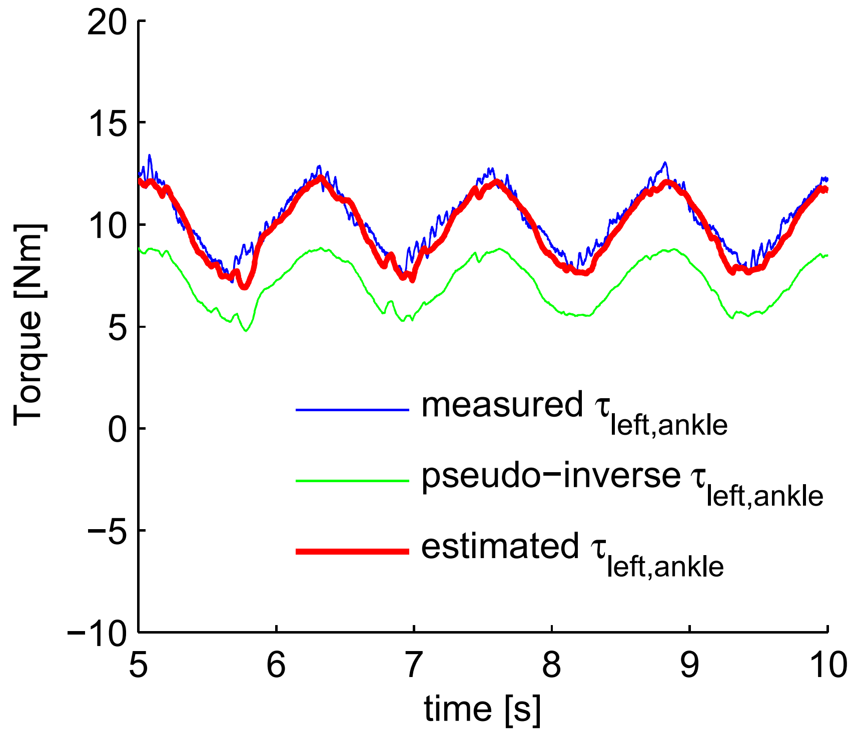
Joint torque at left knee $\tau_{L,knee}$



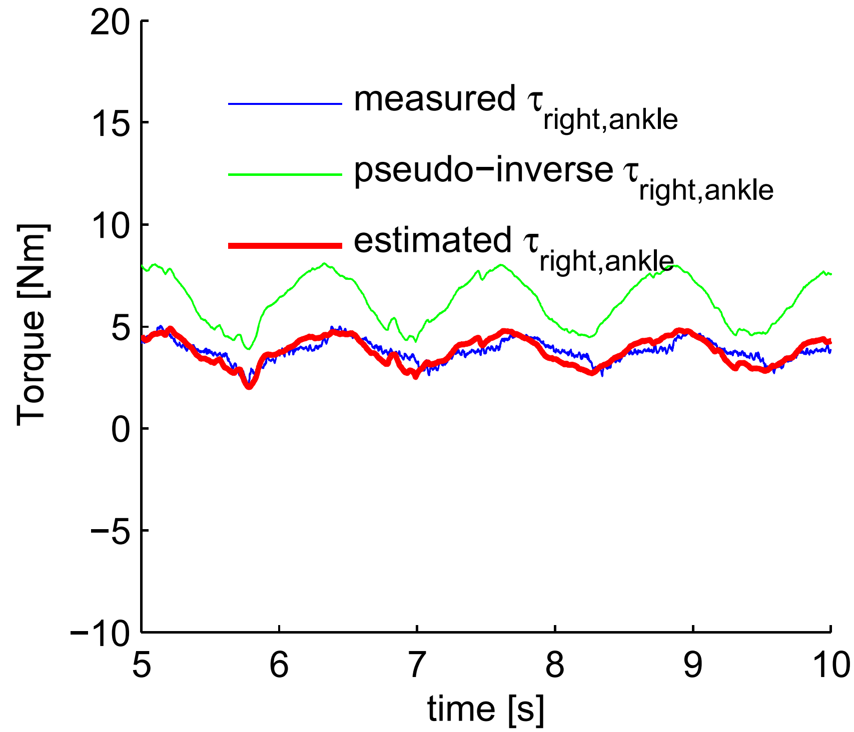
Joint torque at right knee $\tau_{R,knee}$

Results: Configuration 2

Torques at the ankle



Joint torque at left ankle $\tau_{L,ankle}$



Joint torque at right ankle $\tau_{R,ankle}$

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Conclusion

- Under-determinacy can be resolved in a physically consistent way by taking the stiffness model into account
- The method is quick to execute in a real-time controller
- The GRF estimation is sensitive to modelling errors
- However, the effect of modelling errors are shown to be small
- The method is shown to work under the dynamic conditions
- Energy stored in the system is minimized $\Rightarrow$ safe for human interaction

Thank you!