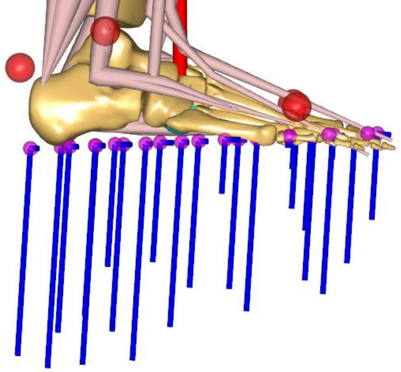
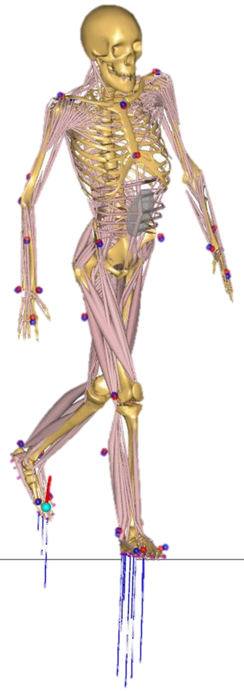


The webcast will start in a few minutes….



Ground reaction force prediction

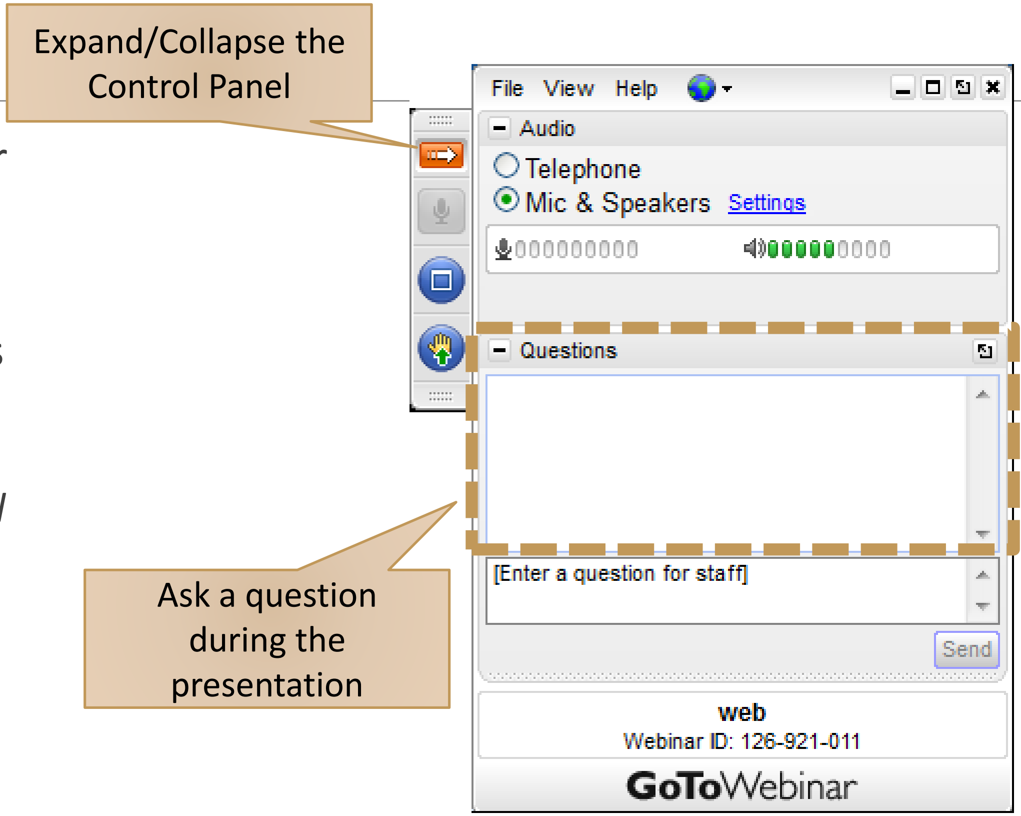
WITH THE ANYBODY MODELING SYSTEM

Control Panel

The Control Panel appears on the right side of your screen.

Submit questions and comments via the Questions panel.

> *Questions will be addressed at the end of the presentation. If your question is not addressed we will do so by email.*



Morten Enemark Lund
Application Engineer
AnyBody Technology

Outline

Introduction by the Host

GRF prediction in sports activities

- *by Sebastian Skals*

Technical explanation

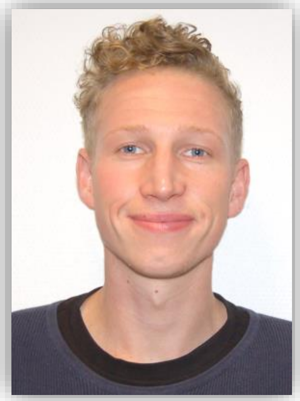
- by Michael Skipper Andersen

Hands on:

- Adding GRF prediction to an existing Anybody MoCap model

Questions and answers

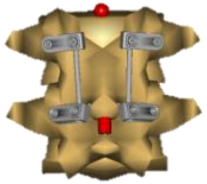
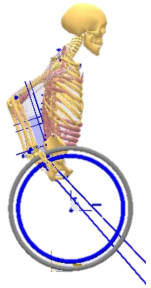
Presenters:

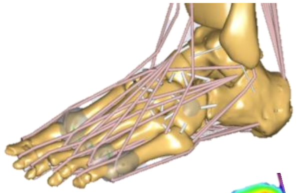
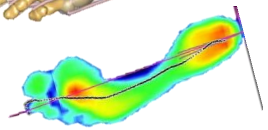
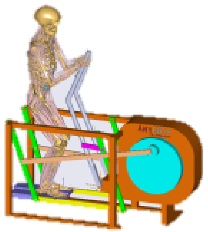


Sebastian Skals, M.Sc.
Research Assistant
National Research Centre for the Working Environment
Danish Ministry of Employment.
Denmark

Michael Skipper Andersen, Ph.D.
Associate professor
Department of Mechanical and Manufacturing Engineering.
Aalborg University
Denmark

Who is AnyBody?

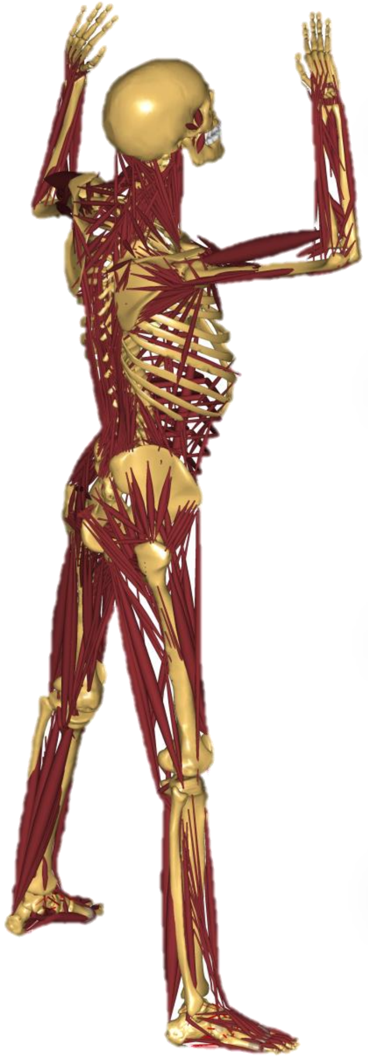
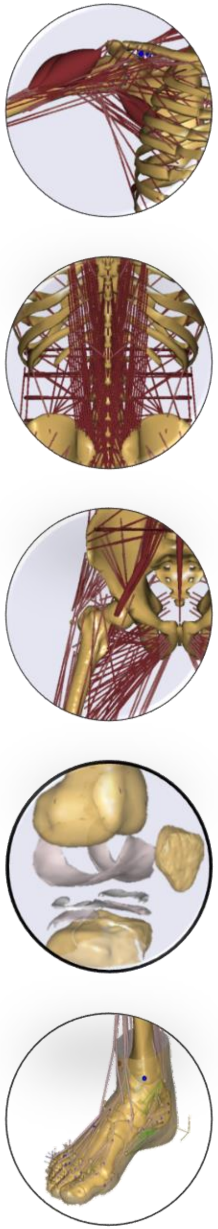




<u>AnyBody Technology</u>
(Aalborg, DK; Boston, US)

- *AnyBody Modeling System*
- *Licenses, Training, Support*
- *Consulting*

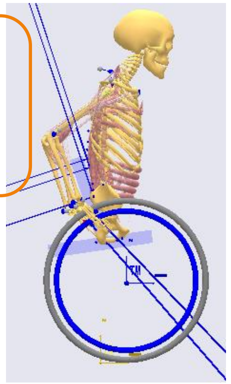
<u>AnyBody Knowledge Centers</u>

- *DK: Aalborg University - Prof. Rasmussen*
    - *Biomechanics, Ergonomics, Sport, Automotive*
- *US: Colorado School of Mines – Prof. Petrella*
    - *Biomechanics, Orthopedics, Sport*
- *GER: OTH Regensburg – Prof. Dendorfer*
    - *Biomechanics, Orthopedics, Gait*

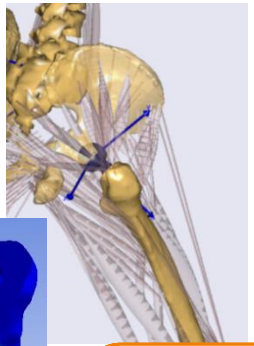
Gait Application
AnyGait

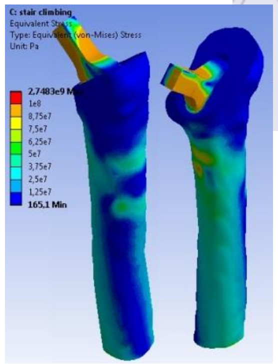
Product Design
Optimization



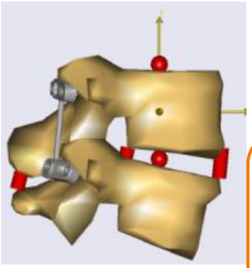
Ergonomic Analysis
and Documentation

AnyBody
Modeling System



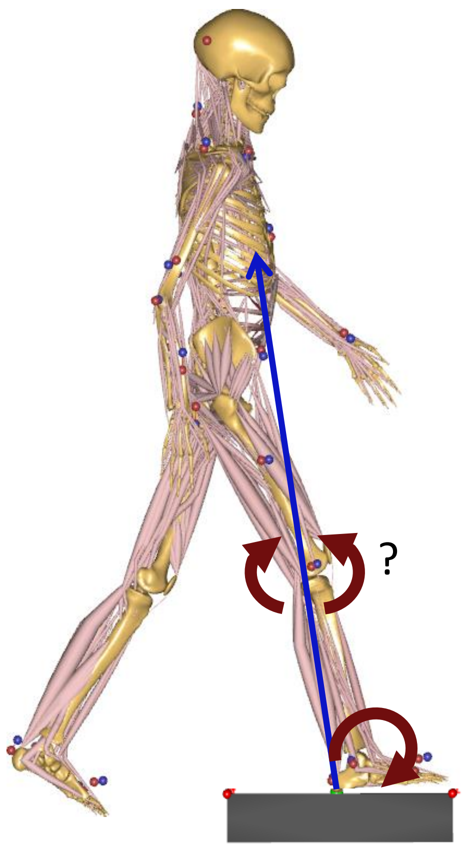


Physiological Load
Cases for Finite
Element Analysis



Surgical Planning, -
Evaluation & -Failure
Analysis

Modeling with measured forces



Boundary conditions are necessary for inverse dynamic analysis.

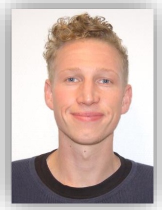
In MoCap models this is provided by force plates.

*What if **no measurements are available**?*

Ground reaction force prediction

IN SPORTS ACTIVITIES

Sebastian Skals, M.Sc.
Research Assistant
National Research Centre for the Working Environment
Danish Ministry of Employment.

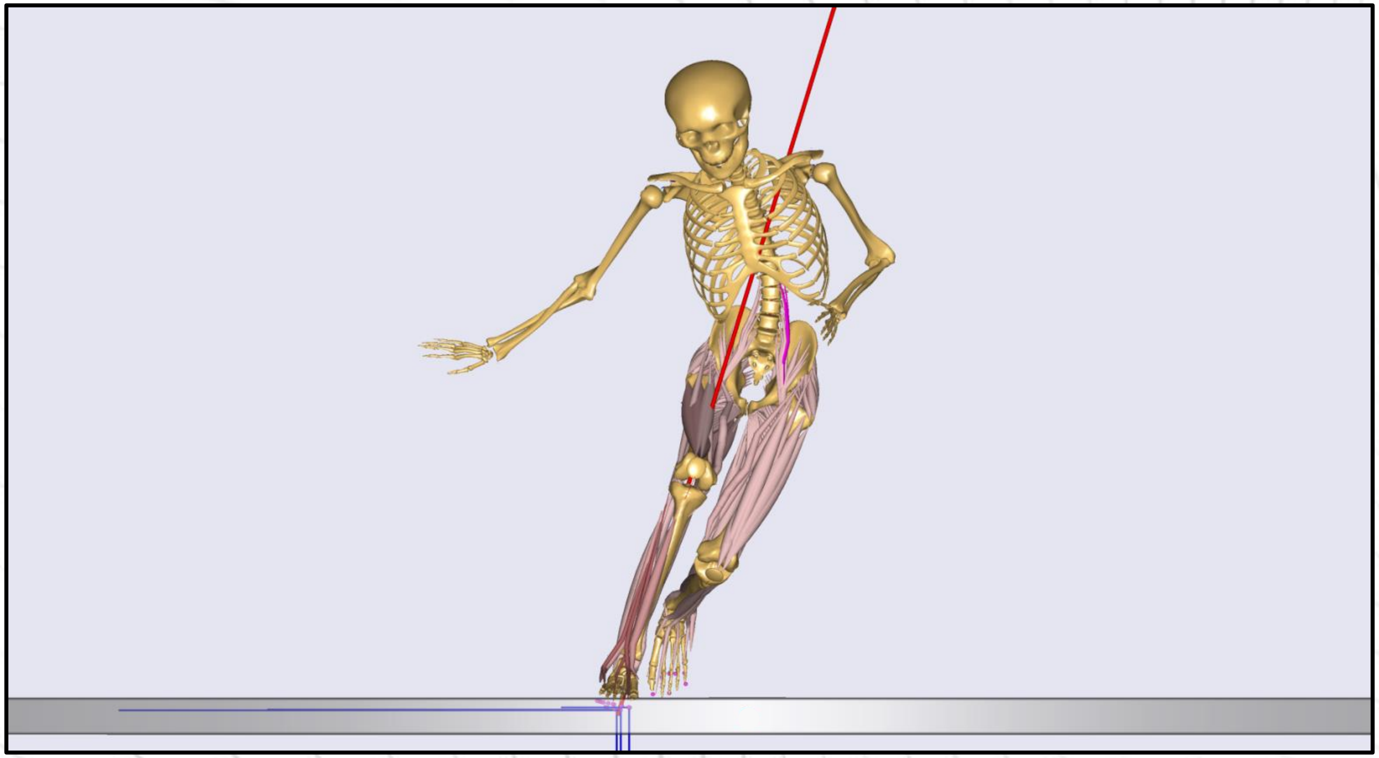


ANYBODY TECHNOLOGY

PREDICTION OF GROUND REACTION FORCES AND MOMENTS DURING SPORTS-RELATED MOVEMENTS

SEBASTIAN L. SKALS[1], MOONKI JUNG[2], MICHAEL DAMSGAARD[2], MICHAEL S. ANDERSEN[3]

[1]DEPARTMENT OF HEALTH SCIENCE AND TECHNOLOGY, AALBORG UNIVERSITY, AALBORG, DENMARK
[2]ANYBODY TECHNOLOGY A/S, AALBORG, DENMARK
[3]DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING, AALBORG UNIVERSITY, AALBORG, DENMARK



AALBORG UNIVERSITY
DENMARK

ANYBODY RESEARCH PROJECT

INTRODUCTION

Inverse Dynamic Analysis (IDA) of musculoskeletal models

- Applied in many fields, e.g., sports biomechanics

- Estimation of muscle, ligament, and joint forces

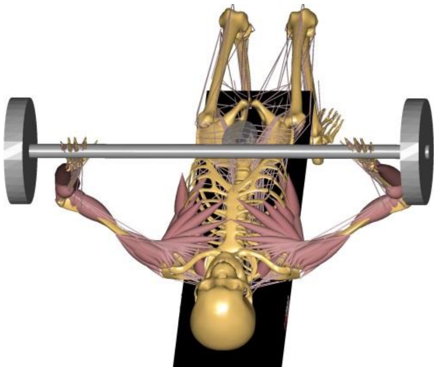
1) Top-down

  - Under-determinate during double support

2) Bottom-up

  - Force plate measurements

    → Residual forces and moments



ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

INTRODUCTION

Typical solutions to these issues

1) Minimise residuals through optimisation methods

2) Estimate/distribute GRF&Ms under both feet

Proposed solutions for 2:

- Minimise joint moments (Audu et al. 2003, 2007)
    - Only standing positions, not movement

- *Artificial Neural Network* (Eel Oh et al. 2013, Choi et al. 2013)
    - Comprehensive analysis necessary to determine input

- **Dynamic contact model and muscle recruitment (Fluit et al. 2014)**
    - Universal method
    - Scaled model and kinematic data only
    - Validated for activities of daily living

INTRODUCTION

None of the existing methods have been validated for sports-related movements.

- Force plate measurements particularly limiting
- Larger accelerations and forces
- Complex movement patterns and contact conditions

AIM: To evaluate the accuracy of the method of Fluit et al. (2014) to predict GRF&Ms during sports-related movements.

- IDA of movements common for sports and recreational exercise
- Compare predicted GRF&Ms to measured data
- Compare joint kinetics between models

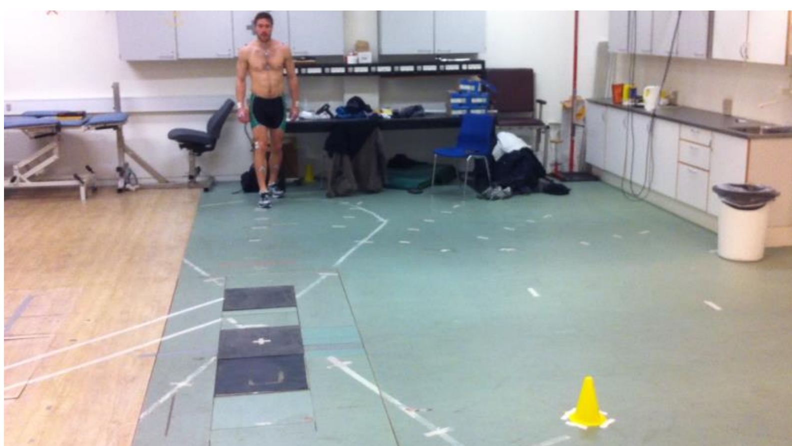
EXPERIMENTAL PROCEDURES

- Eight male and two female subjects
  (age: 25.70 ± 1.49 years, height: 180.80 ± 7.39 cm, weight: 76.88 ± 10.37 kg)

- Five sports-related movements:

  - Running at a self-selected pace
  - Backwards running
  - Side-cut
  - Vertical jump
  - Acceleration from a standing position (ASP)

- Varying force characteristics and double/single support



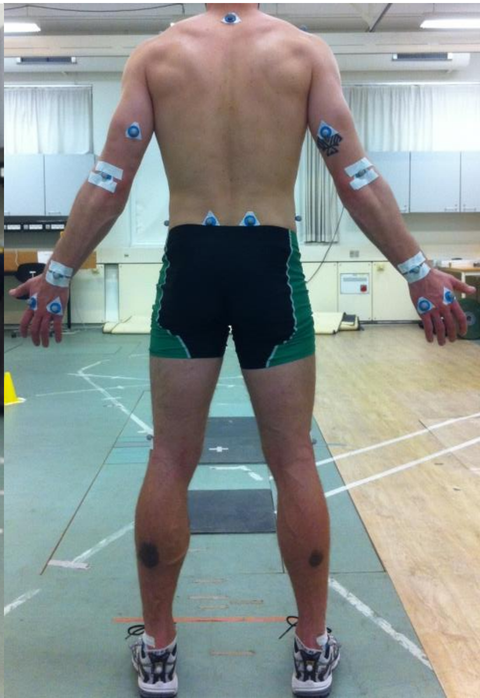
ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

EXPERIMENTAL PROCEDURES

Marker-based motion analysis:

- Eight infrared cameras sampling at 250 Hz (Oqus 300 series)
- Qualisys Track Manager v. 2.9
- Two AMTI force plates sampling at 2000 Hz
- 35 reflective markers
    - 29 placed on the body
    - 3 on each running shoe
- Data low-pass filtered at 15 Hz



ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

MUSCULOSKELETAL MODELS

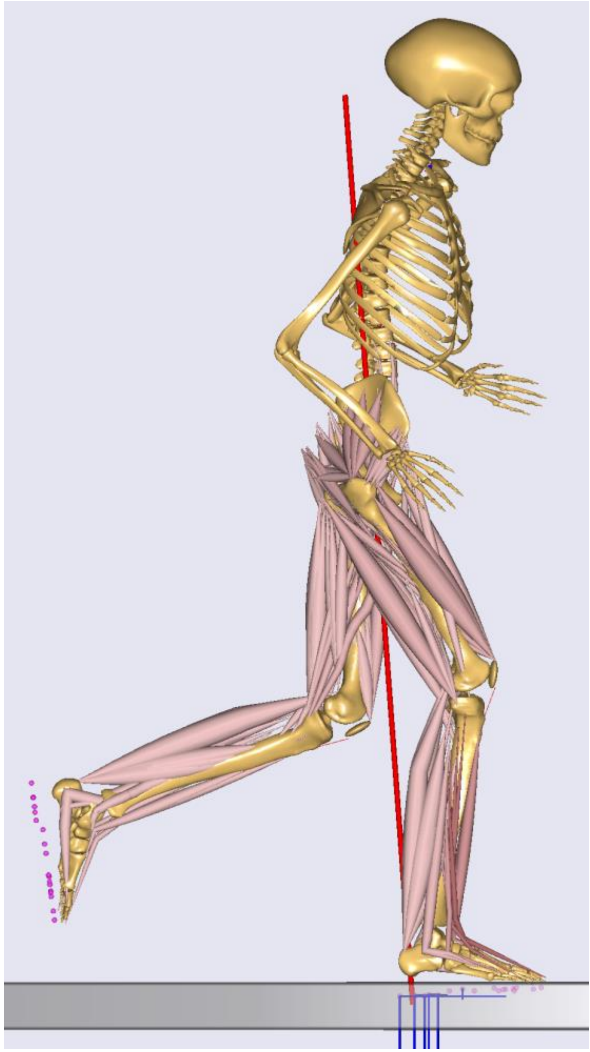
Based on the *GaitFullBody* template from the AnyBody Managed Model Repository v. 1.6.3

Model scaling and kinematics
(Andersen et al. 2009, 2010)

- Adjusts segment lengths and marker coordinates
- Minimises the sum of marker residuals

Inverse Dynamic Analysis

- Twente Lower Extremity Model
  (Horsman et al., 2007)
- Simple constant strength muscles
- Quadratic muscle recruitment



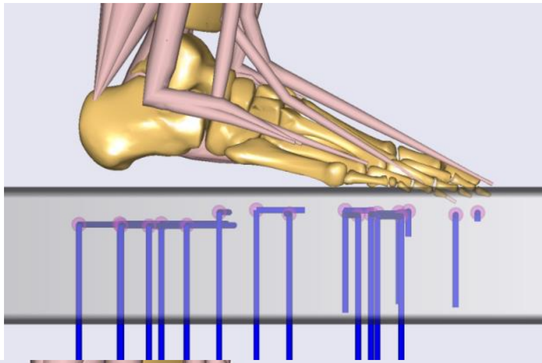
ANYBODY RESEARCH PROJECT

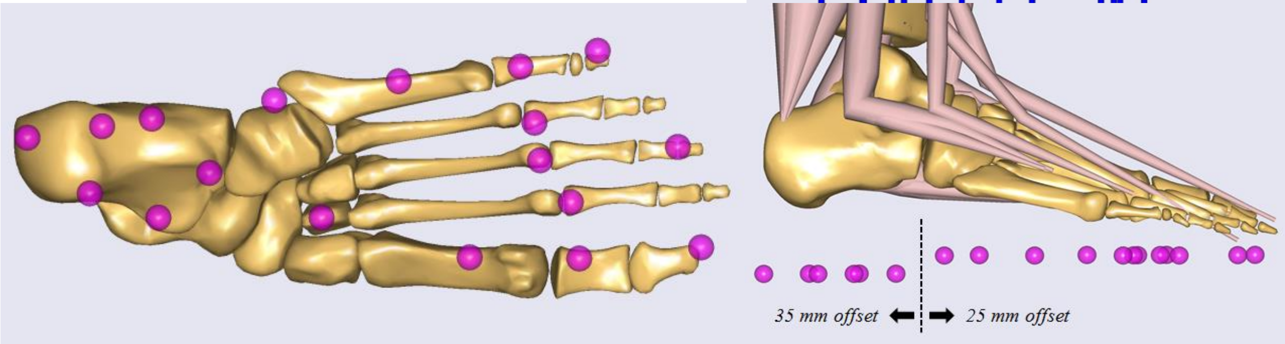
AALBORG UNIVERSITY DENMARK

PREDICTION OF GRF&Ms

Method of Fluit et al. (2014) adopted, but alterations were made in an attempt to improve the method.

- 18 contact points defined under each foot
- Five artificial muscle-like actuators in each contact point
- F_{max}, z_{limit}, and v_{limit} (contact parameters)
- Smoothing function implemented
- Solved as part of muscle recruitment algorithm

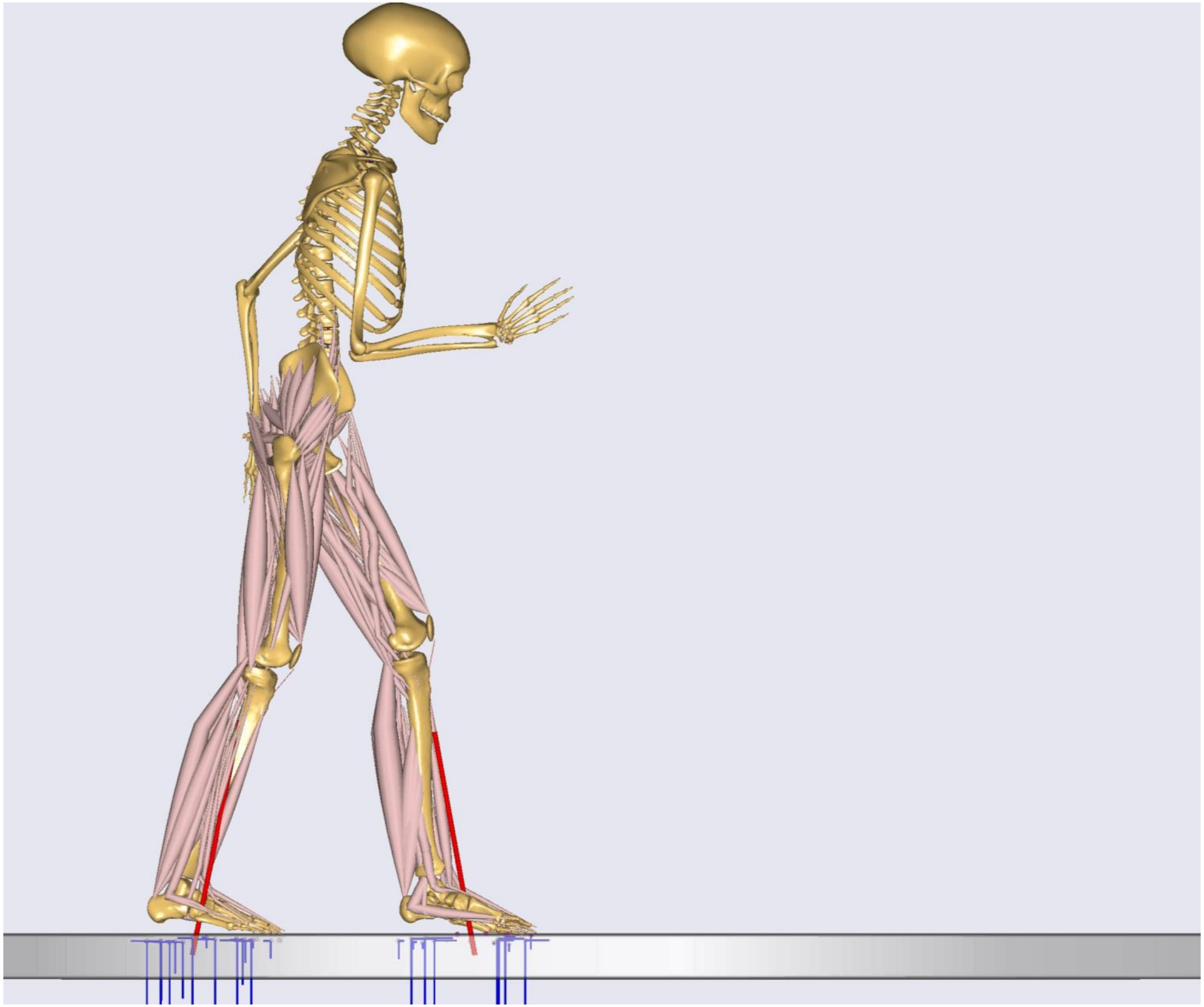




AnyBody RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

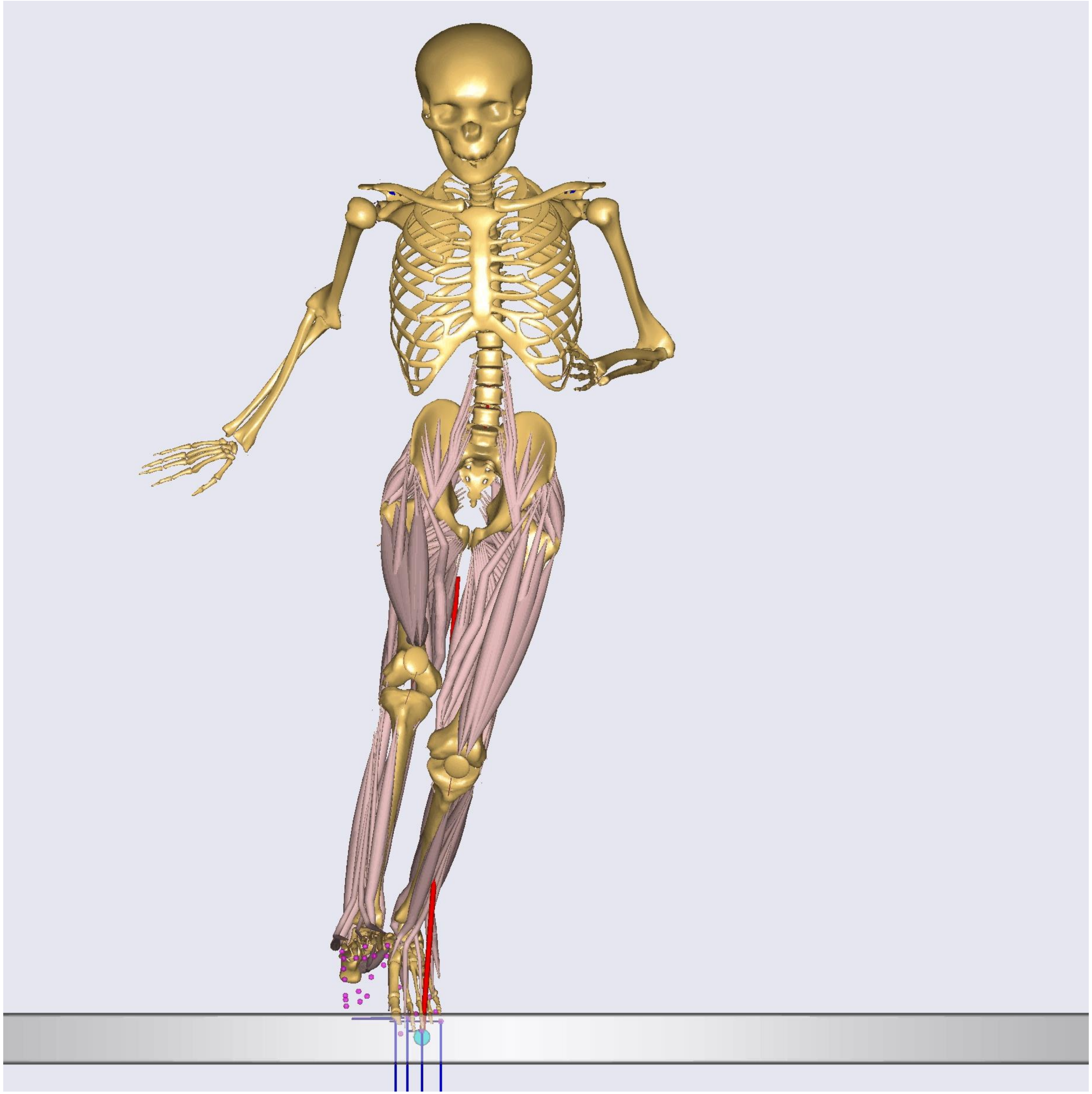
RESULTS



ANYBODY™
RESEARCH PROJECT

AALBORG UNIVERSITY
DENMARK

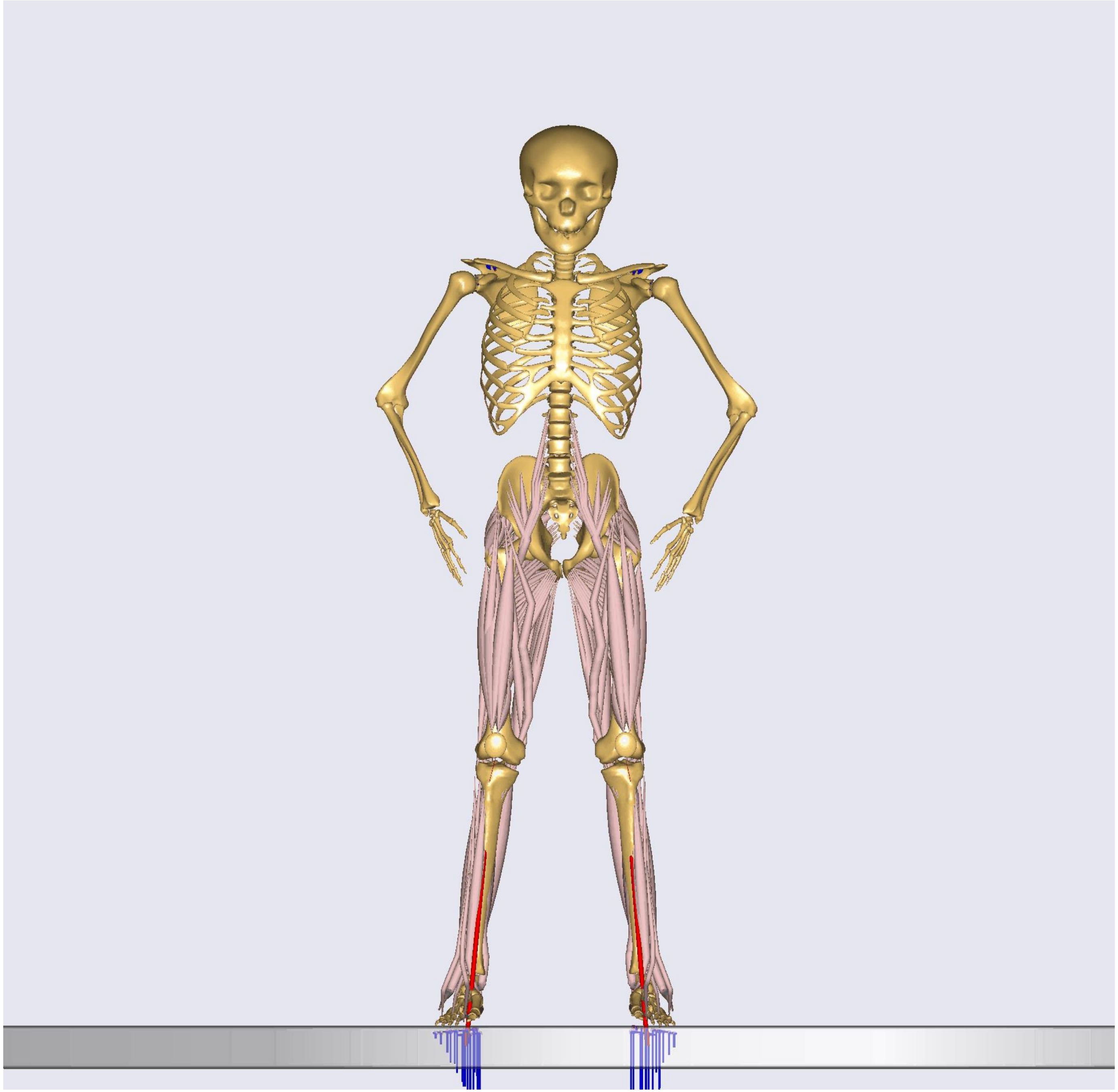
RESULTS



ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY
DENMARK

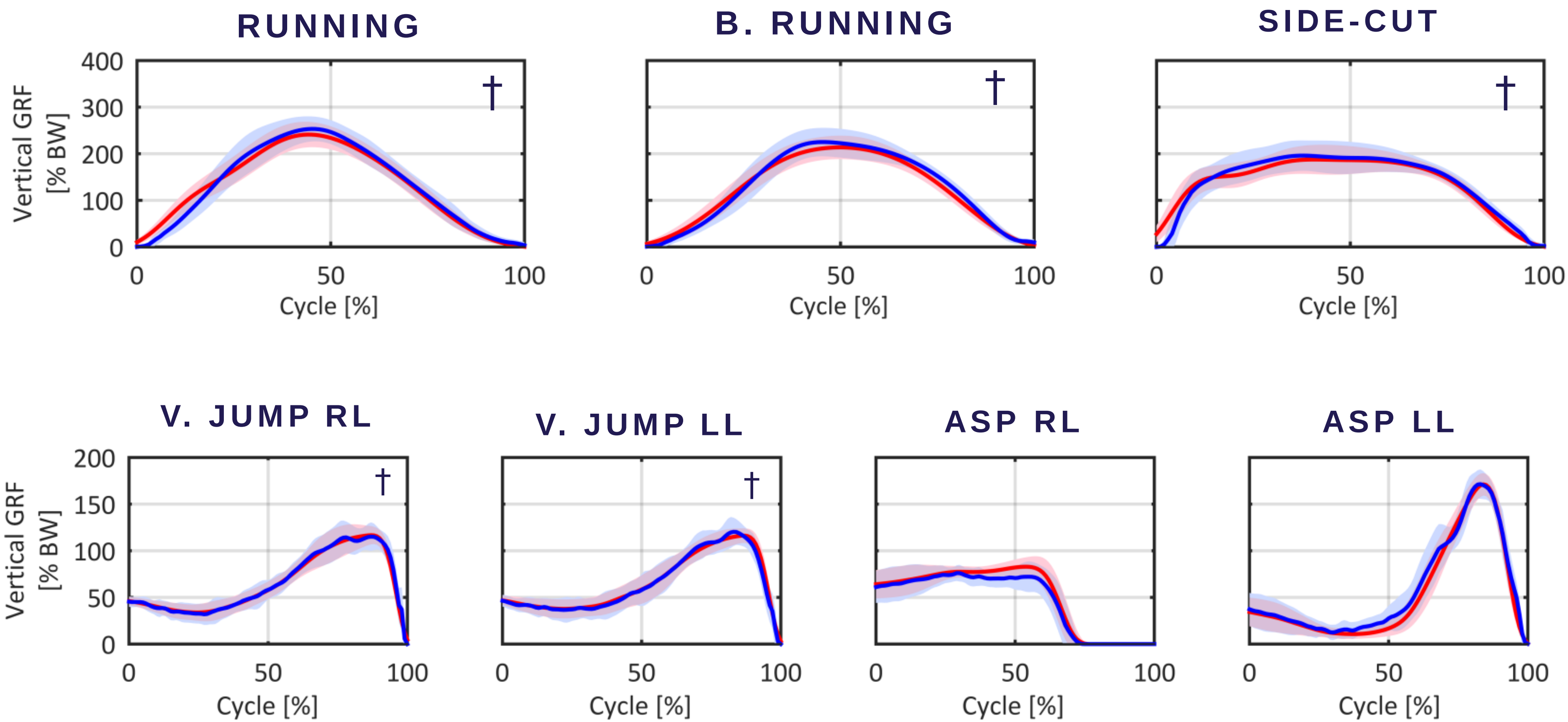
RESULTS



ANYBODY
RESEARCH PROJECT

AALBORG UNIVERSITY
DENMARK

RESULTS



***r* ranging from 0.97 to 0.99, median 0.99**

RED: Measured GRF&Ms

BLUE: Predicted GRF&Ms

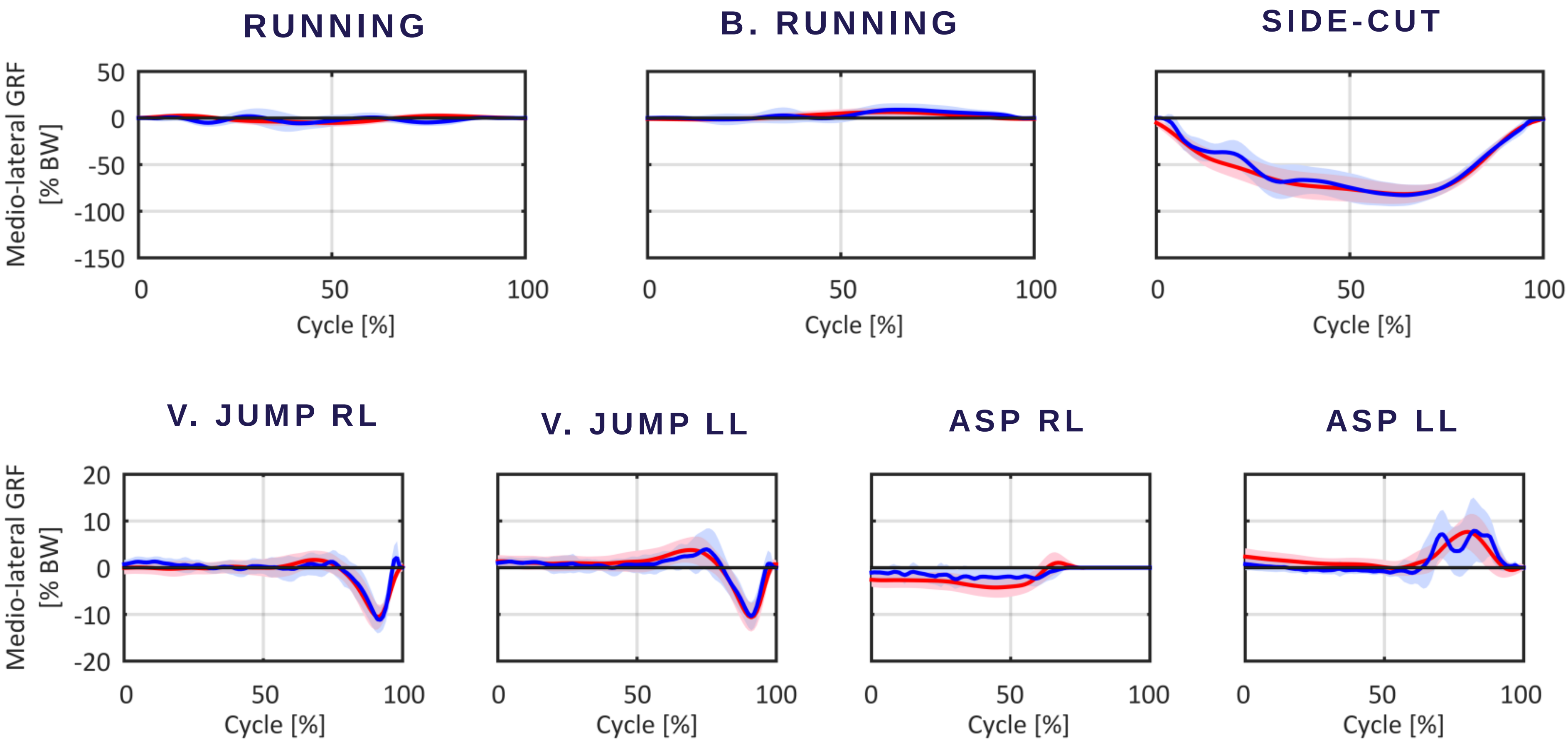
Shaded areas: ± 1 STD

† = sig. diff. peak forces

ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

RESULTS



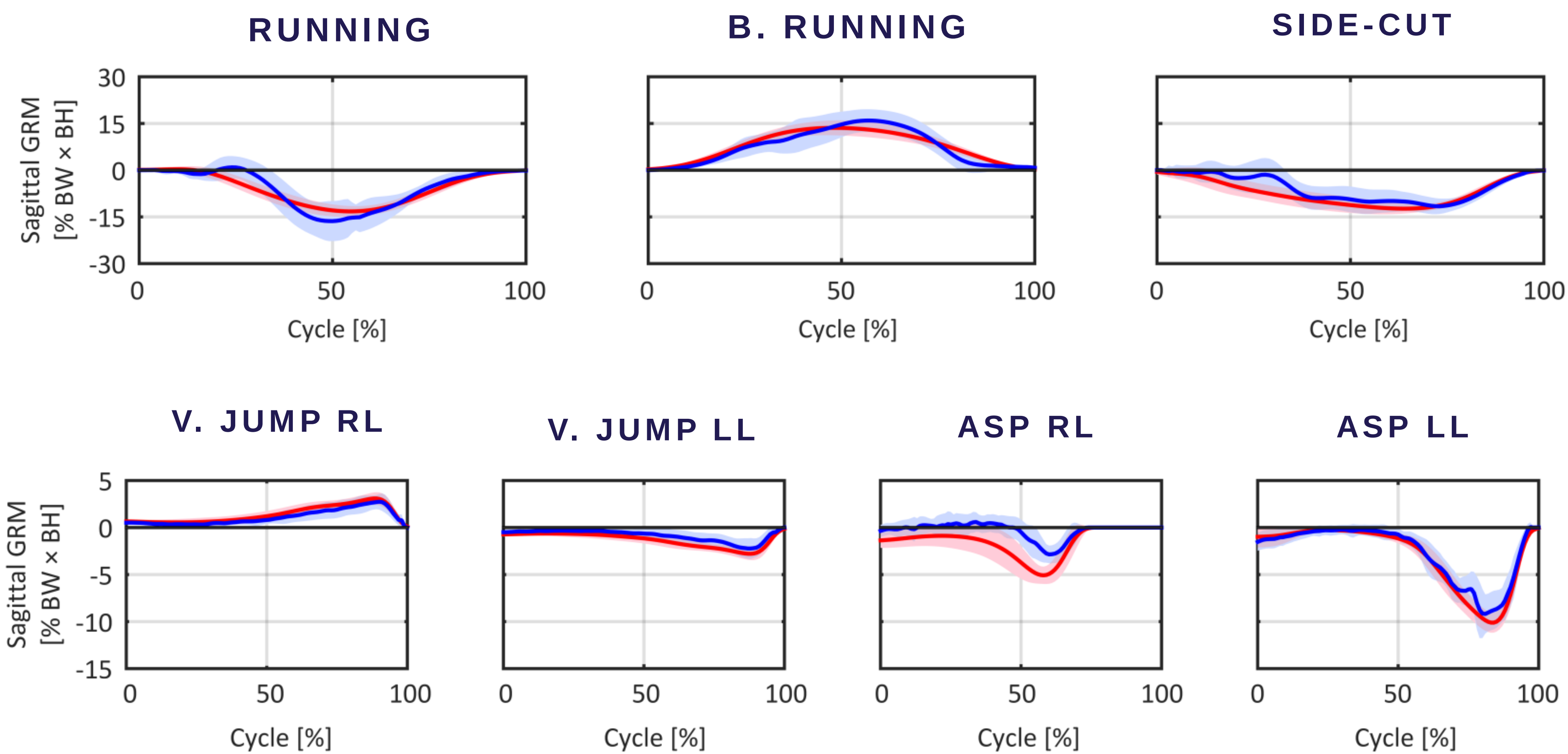
ANYBODY RESEARCH PROJECT

***r* ranging from 0.13 to 0.96, median 0.61**

RED: Measured GRF&Ms
BLUE: Predicted GRF&Ms
Shaded areas: ± 1 STD

AALBORG UNIVERSITY
DENMARK

RESULTS



ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

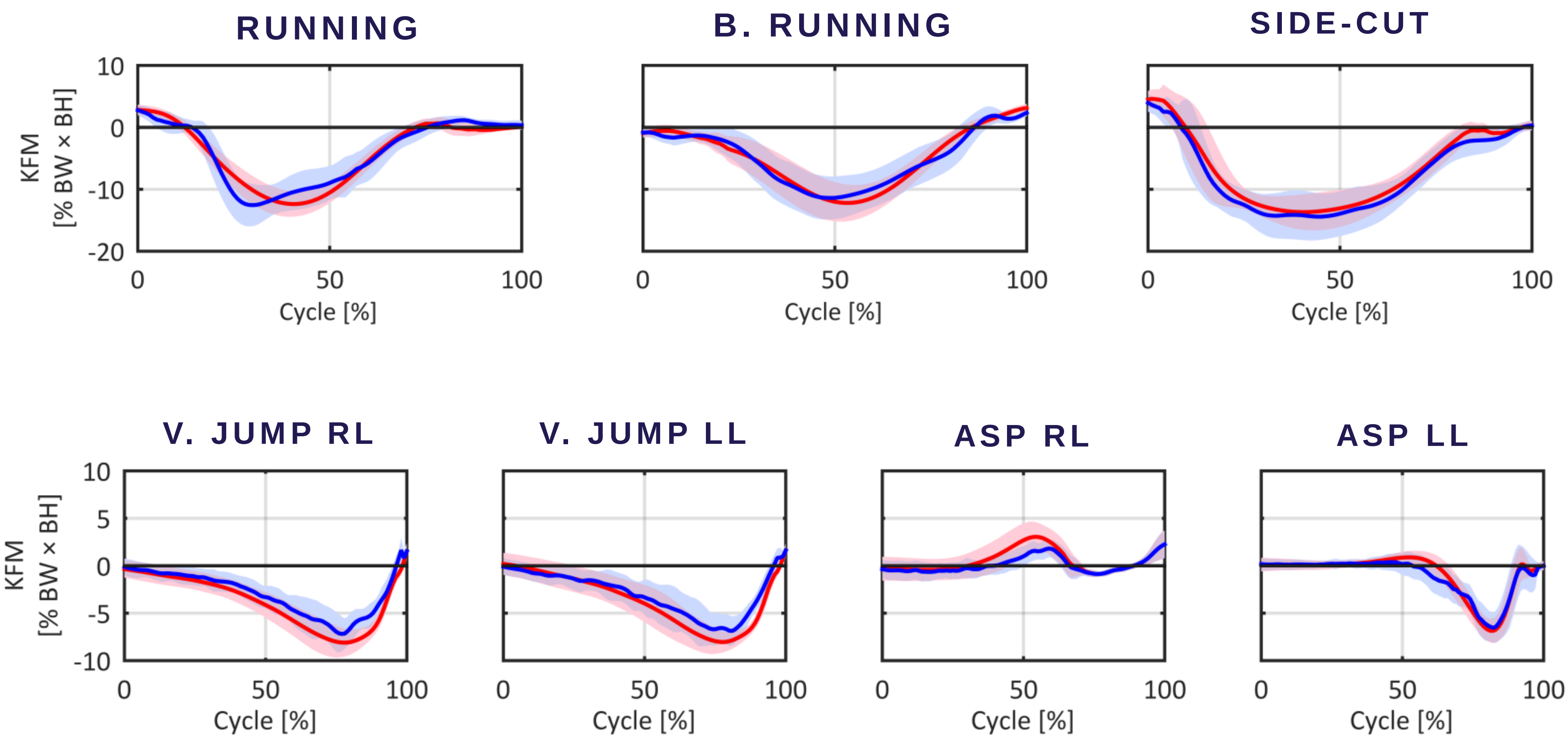
***r* ranging from 0.69 to 0.95, median 0.87**

RED: Measured GRF&Ms

BLUE: Predicted GRF&Ms

Shaded areas: ± 1 STD

RESULTS



***r* ranging from 0.86 to 0.95, median 0.94**

RED: Measured GRF&Ms

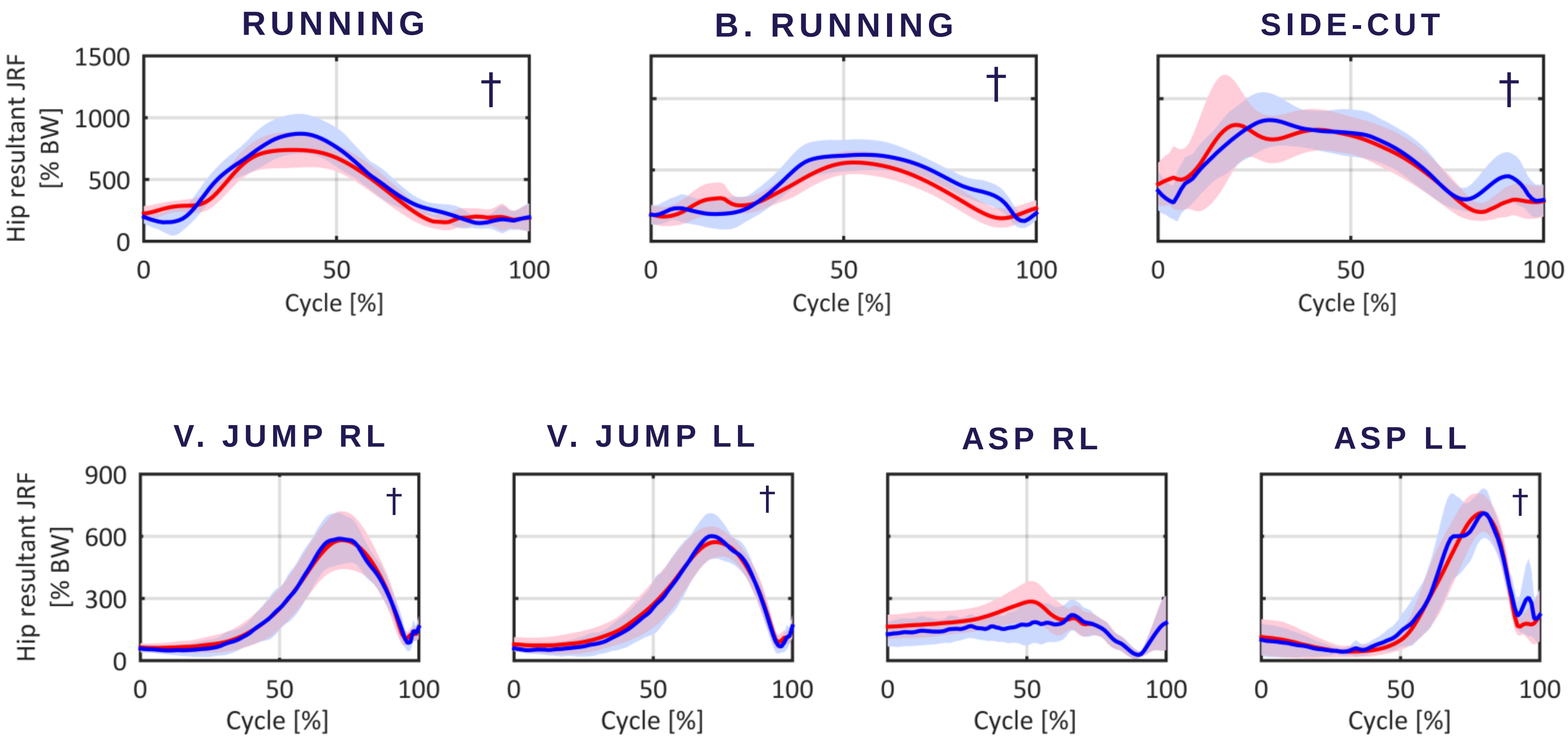
BLUE: Predicted GRF&Ms

Shaded areas: ± 1 STD

ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

RESULTS



ANYBODY RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

***r* ranging from 0.78 to 0.94, median 0.94**

RED: Measured GRF&Ms
BLUE: Predicted GRF&Ms
Shaded areas: ± 1 STD

† = sig. diff. peak forces

DISCUSSION

- Comparable results for vertical GRFs, joint flexion moments, and resultant JRFs across all movements

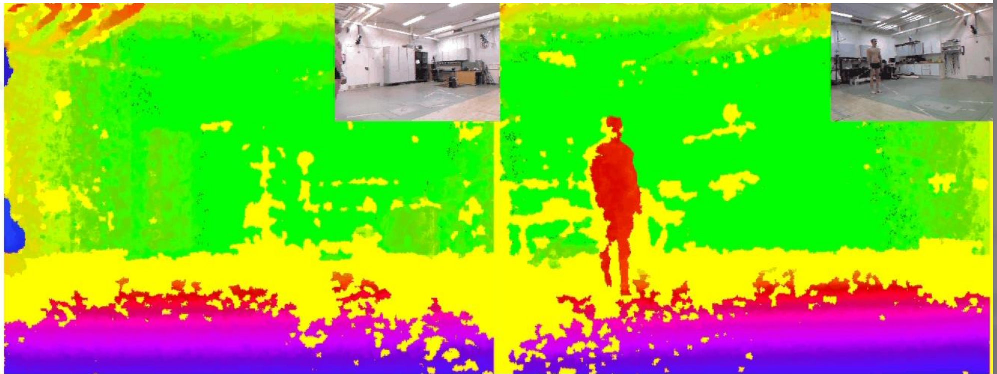
- Majority of peak forces significantly different
  - Adjusting contact parameters a possible solution

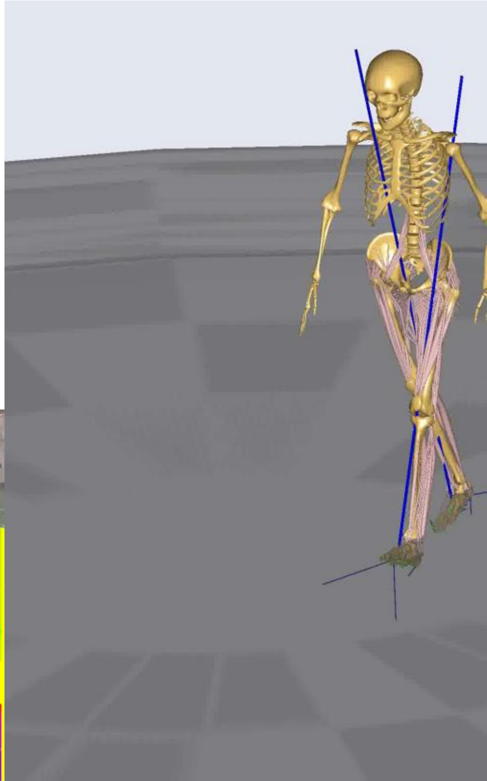
- Discrepancies identified for, e.g., transverse GRM and HERM
  - Signal-to-noise ratio
  - Simple knee model (hinge joint)

- Areas to improve:
  - Foot-ground contact determination
  - More detailed knee and foot model
  - Sensitivity analysis on contact parameters

CONCLUSION AND FUTURE WORK

- Could be used instead of force plate data
- Alternative to multi-setting instrumentation of force plates
  - Outdoor environments
  - Workplaces
  - Treadmills
- Combination with other motion analysis systems, e.g.,
  - Electromagnetic tracking systems
  - Accelerometers/gyroscopes
  - Marker-less systems, e.g., Sandau et al. (2014)
- Interface between MLS and AnyBody (Skals et al. 2014)





AnyBody RESEARCH PROJECT

AALBORG UNIVERSITY DENMARK

PREDICTION OF GROUND REACTION FORCES AND MOMENTS DURING SPORTS-RELATED MOVEMENTS

SEBASTIAN L. SKALS[1], MOONKI JUNG[2], MICHAEL DAMSGAARD[2], MICHAEL S. ANDERSEN[3]

[1]DEPARTMENT OF HEALTH SCIENCE AND TECHNOLOGY, AALBORG UNIVERSITY, AALBORG, DENMARK
[2]ANYBODY TECHNOLOGY A/S, AALBORG, DENMARK
[3]DEPARTMENT OF MECHANICAL AND MANUFACTURING ENGINEERING, AALBORG UNIVERSITY, AALBORG, DENMARK

REFERENCES

AUDU, M. L., R. F. KIRSCH, AND R. J. TRIOLO. A COMPUTATIONAL TECHNIQUE FOR DETERMINING THE GROUND REACTION FORCES IN HUMAN BIPEDAL STANCE. J. APPL. BIOMECH. 19:361–371, 2003.

AUDU, M. L., R. F. KIRSCH, AND R. J. TRIOLO. EXPERIMENTAL VERIFICATION OF A COMPUTATIONAL TECHNIQUE FOR DETERMINING GROUND REACTIONS IN HUMAN BIPEDAL STANCE. J. BIOMECH. 40:1115–1124, 2007.

CHOI, A., J.-M. LEE, AND J. H. MUN. GROUND REACTION FORCES PREDICTED BY USING ARTIFICIAL NEURAL NETWORK DURING ASYMMETRIC MOVEMENTS. INT. J. PRECIS. ENG. MANUF. 14:475–483, 2013.

EEL OH, S., A. CHOI, AND J. H. MUN. PREDICTION OF GROUND REACTION FORCES DURING GAIT BASED ON KINEMATICS AND A NEURAL NETWORK MODEL, J. BIOMECH. 46:2372–2380, 2013.

FLUIT, R., M. S. ANDERSEN, S. KOLK, N. VERDONSCHOT, AND H. F. J. M. KOOPMAN. PREDICTION OF GROUND REACTION FORCES AND MOMENTS DURING VARIOUS ACTIVITIES OF DAILY LIVING. J. BIOMECH. 47:2321–2329, 2014.

HORSMAN, M. D. K., H. F. J. M. KOOPMAN, F. C. T. VAN DER HELM, L. P. PROSÉ, AND H. E. J. VEEGER. MORPHOLOGICAL MUSCLE AND JOINT PARAMETERS FOR MUSCULOSKELETAL MODELLING OF THE LOWER EXTREMITY. CLIN. BIOMECH. 22:239–247, 2007.

SANDAU, M., H. KOBLAUCH, T. B. MOESLUND, H. AANÆS, T. ALKJÆR, AND E. B. SIMONSEN. MARKERLESS MOTION CAPTURE CAN PROVIDE RELIABLE 3D GAIT KINEMATICS IN THE SAGITTAL AND FRONTAL PLANE. MED. ENG. PHYS. 36:1168-1175, 2014.

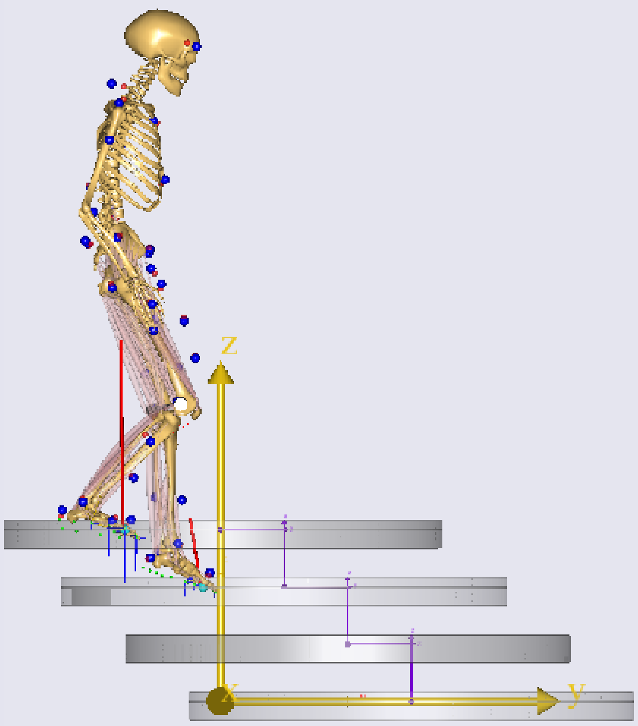
SKALS, S. L., K. M. BENDTSEN, K. P. RASMUSSEN, AND M. S. ANDERSEN. VALIDATION OF MUSCULOSKELETAL MODELS DRIVEN BY DUAL MICROSOFT KINECT SENSOR DATA. IN: 13TH INTERNATIONAL SYMPOSIUM ON 3D ANALYSIS OF HUMAN MOVEMENT, 2014, LAUSANNE, SWITZERLAND.

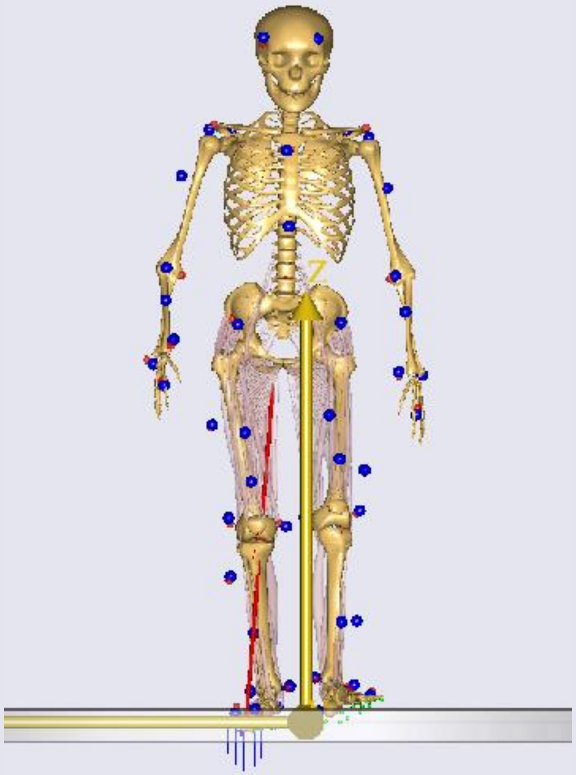
AALBORG UNIVERSITY
DENMARK

ANYBODY
RESEARCH PROJECT

How does it work?

Associate Professor Michael Skipper Andersen, PhD
Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark



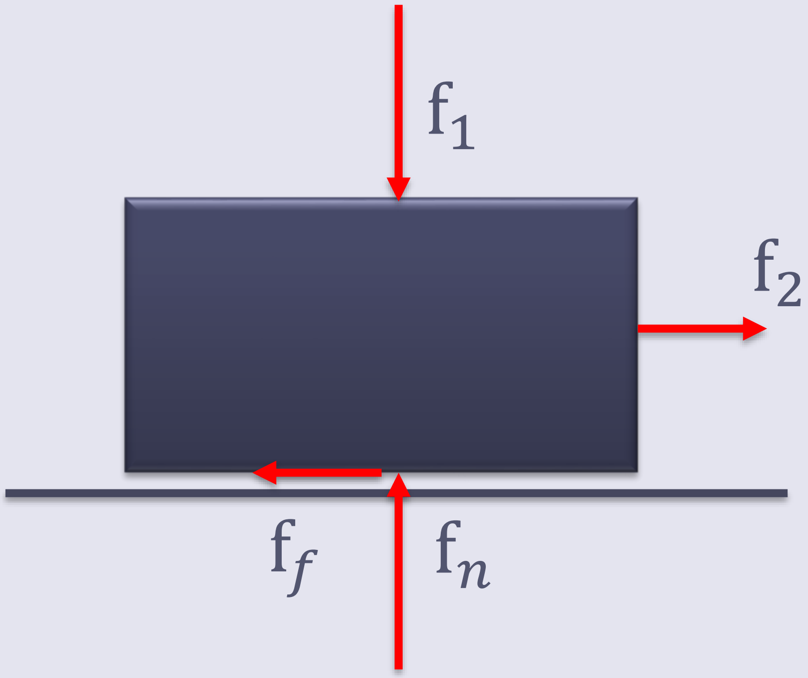


M-Tech

ANYBODY™
RESEARCH PROJECT

Coulomb friction

- Normal force is unilateral.
- Friction force and normal force are perpendicular.
- Friction force is limited by the normal force and friction coefficient.



$$f_n \geq 0$$

$$f_f \leq \mu f_n$$

M-Tech

ANYBODY™ RESEARCH PROJECT

Muscle recruitment

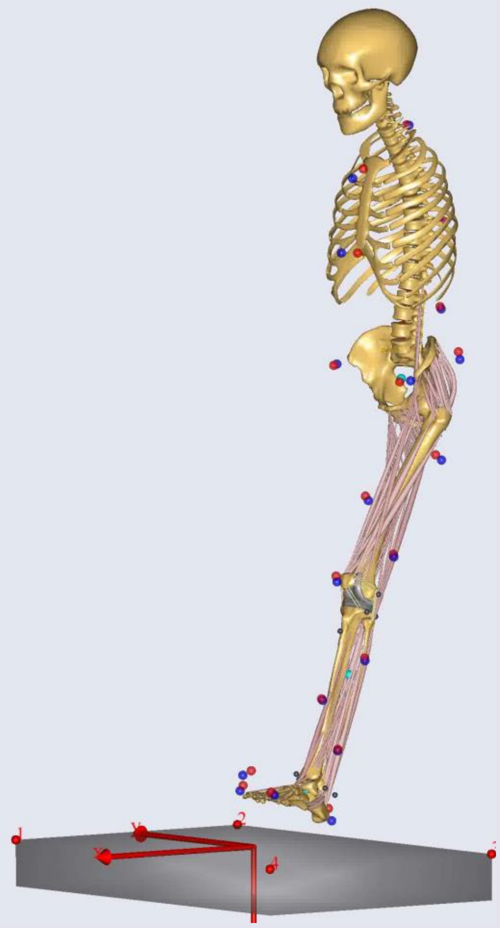
$$\min G\left(\mathbf{f}^{(\mathrm{m})}\right)$$
$$s.t. \quad \mathbf{Cf} = \mathbf{d}$$
$$\mathbf{f}^{(\mathrm{m})} \geq 0$$

- Min/max:

$$G\left(\mathbf{f}^{(\mathrm{m})}\right) = \max_i \left(\frac{f_i^{(m)}}{N_i}\right)$$

- Polynomial:

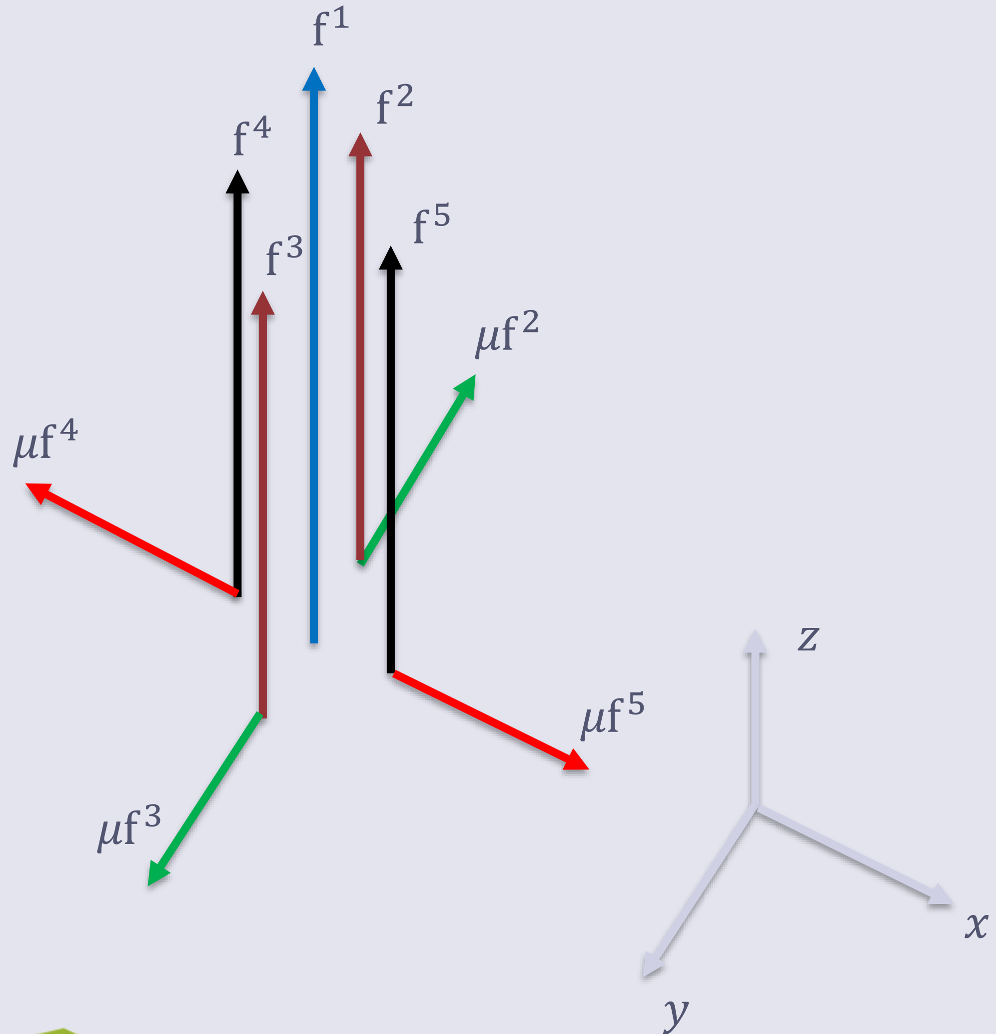
$$G\left(\mathbf{f}^{(\mathrm{m})}\right) = \sum_i^n \left(\frac{f_i^{(\mathrm{m})}}{N_i}\right)^p$$



M-Tech

ANYBODY™ RESEARCH PROJECT

Implementation: forces



$$\mathbf{f}_\mathrm{n} = \mathbf{f}^1+\mathbf{f}^2+\mathbf{f}^3+\mathbf{f}^4+\mathbf{f}^5$$

$$\mathbf{f}_\mathrm{f} = \mu\mathbf{f}^2+\mu\mathbf{f}^3+\mu\mathbf{f}^4+\mu\mathbf{f}^5$$

$$\mathrm{f}^i \geq 0$$

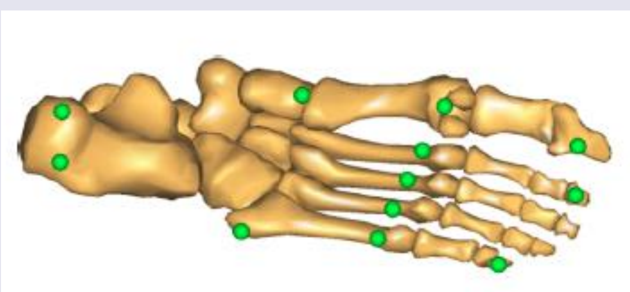
M-Tech

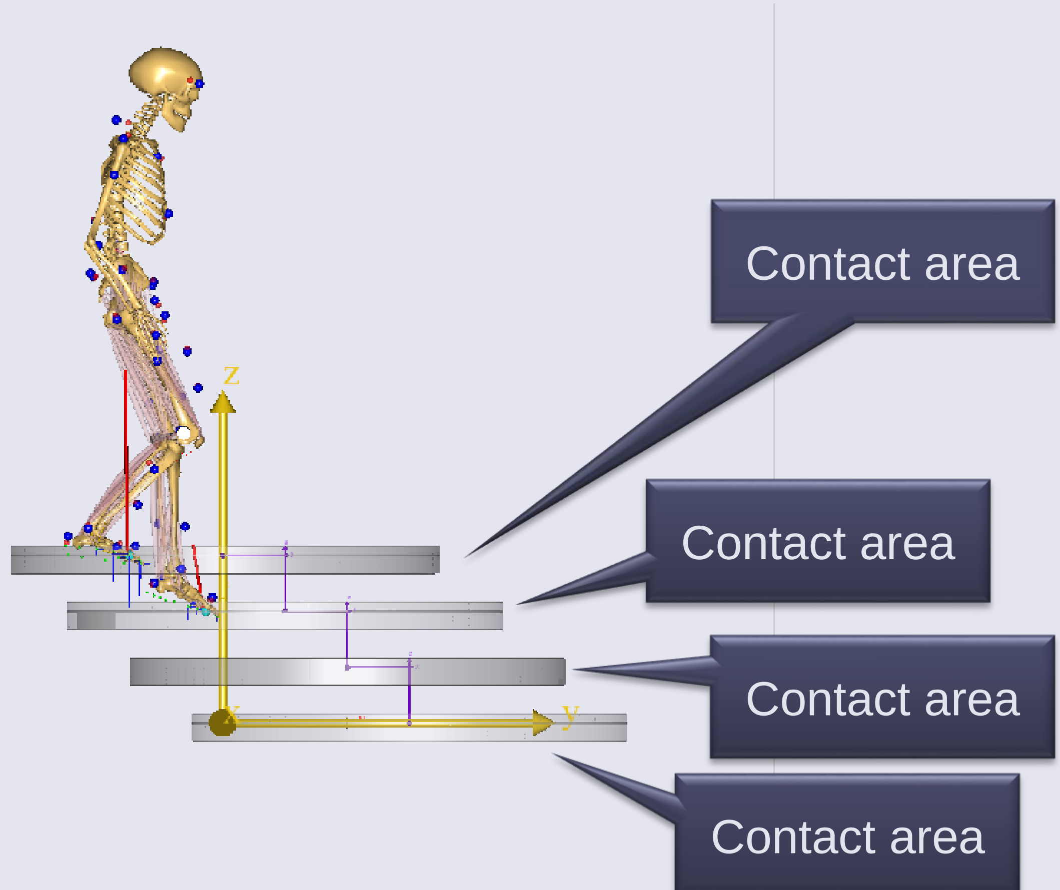
ANYBODY™ RESEARCH PROJECT

Implementation: contact

Contact when:

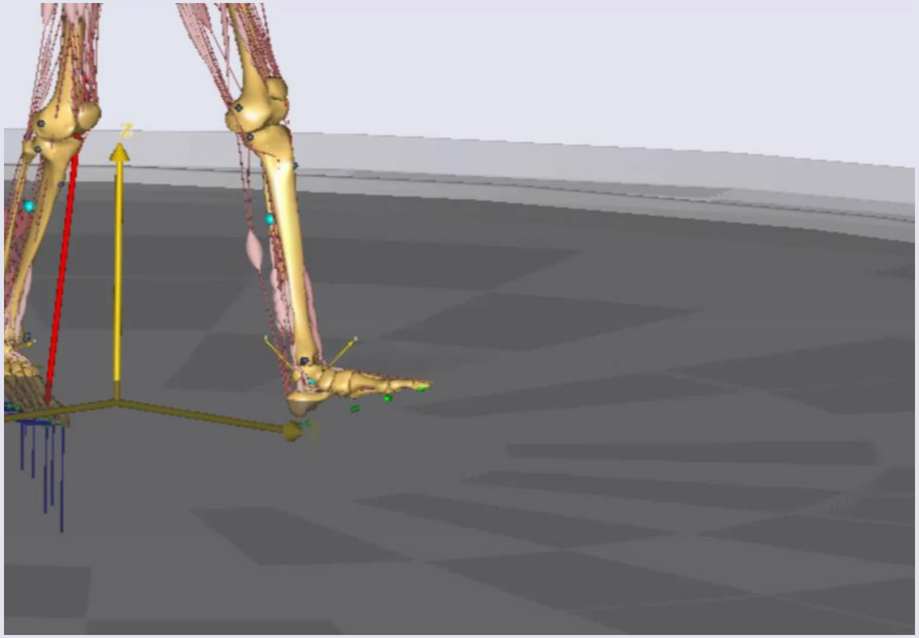
- Node inside contact area.
- Node velocity small.

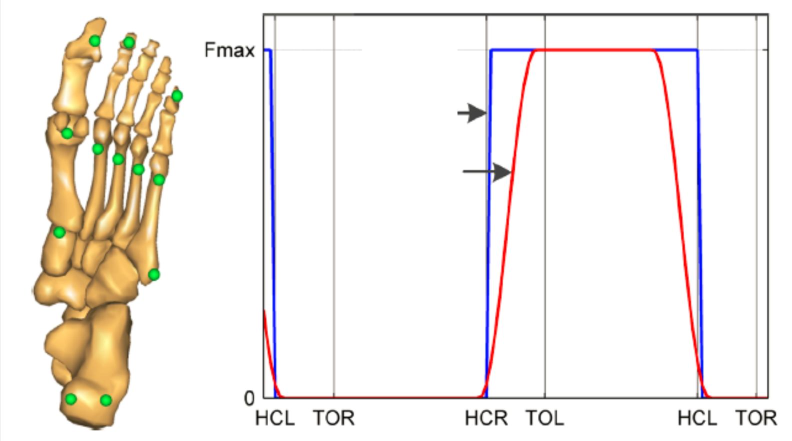




Implementation: contact

- Contact controlled with the ”muscle” strengths
- Transitions are smoothed.
- Smoothing approaches:
    - Post-process kinematics.
    - Smoothing based on node position and velocity.

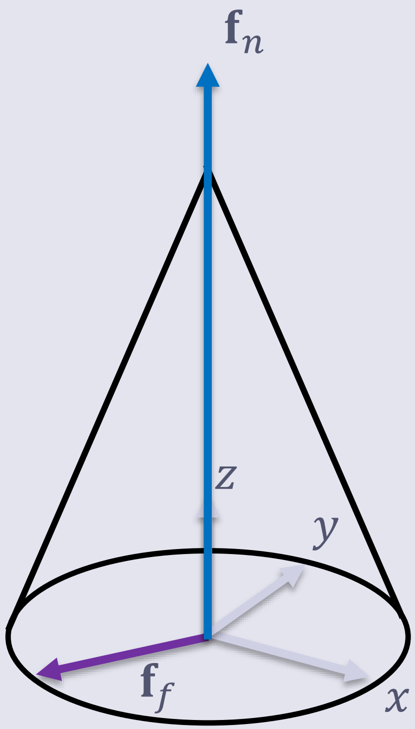




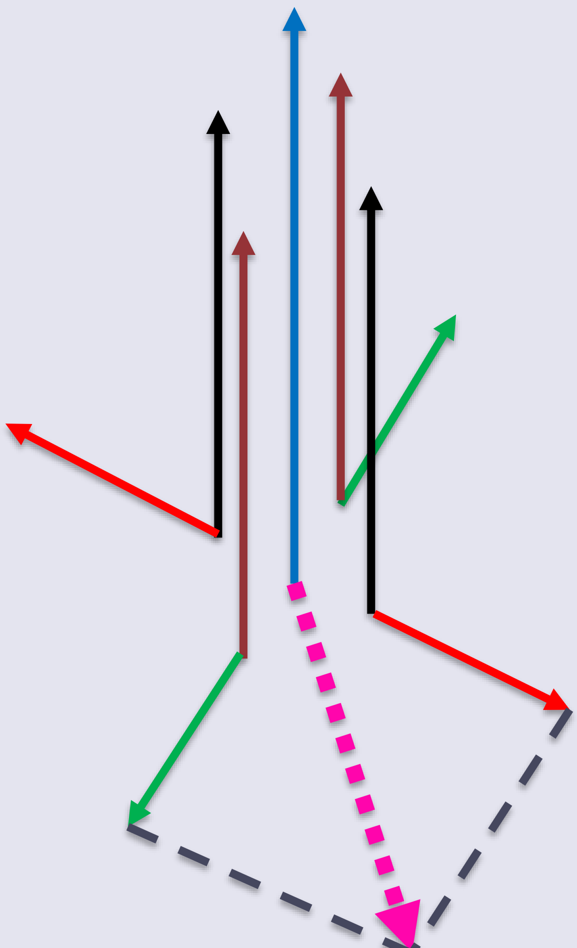
M-Tech

ANYBODY™
RESEARCH PROJECT

Limitation
friction cone vs friction box



$$\|\mathbf{f}_f\| = \sqrt{\mathrm{f}_{f,x}{}^2 + \mathrm{f}_{f,y}{}^2} \leq \mu \|\mathbf{f}_n\|$$



M-Tech

ANYBODY™ RESEARCH PROJECT

Prediction of Ground Reaction Forces in Inverse dynamic simulations

MS Andersen[1] R Fluit[2], S Kolk[3], N Verdonschot[2,4], HFJM Koopman[2], J Rasmussen[1]

[1]Department of Mechanical and Manufacturing Engineering, Aalborg University, Denmark
[2]Laboratory of Biomechanical Engineering, Faculty of Engineering Technology, University of Twente, The Netherlands
[3]Department of Rehabilitation, Radboud University Nijmegen Medical Centre, The Netherlands
[4]Orthopaedic Research Laboratory, Radboud University Nijmegen Medical Centre, The Netherlands

7th World Congress of Biomechanics, Boston, 2014

M-Tech

ANYBODY™ RESEARCH PROJECT

Experimental data

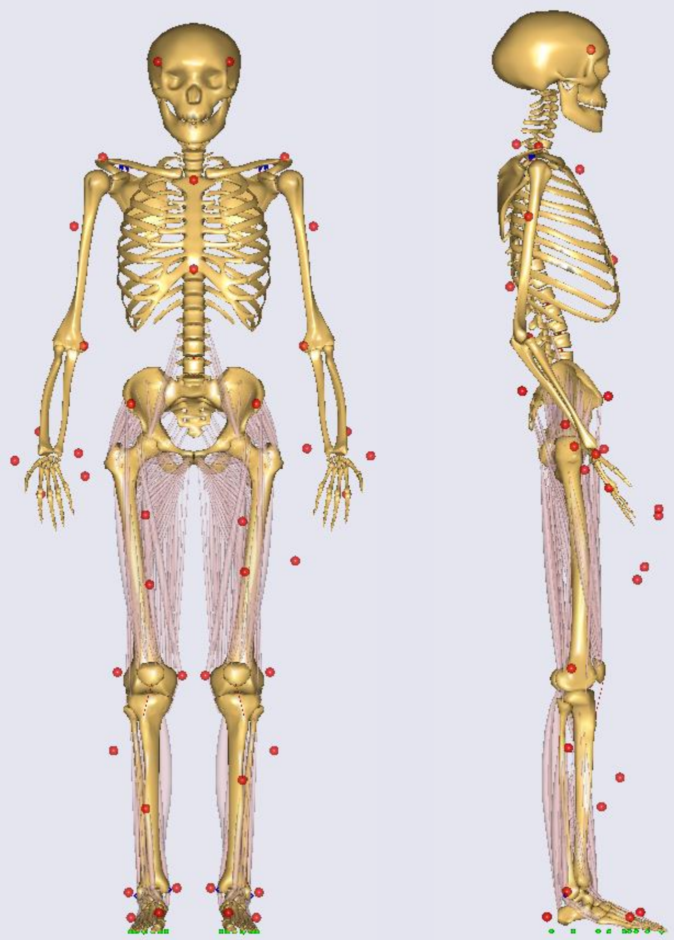
- Nine healthy subjects (4 males and 5 females)
- Gait lab data.
  - Full-body marker set (53 markers).
  - Six-camera Vicon system (100 Hz sampling).
  - Two AMTI forceplates (1000 Hz).
- Activities of daily living (ADLs):
  - Walking at comfortable (CWS) speed
  - Walking at a slow (CWS-30%) speed.
  - Walking at a fast (CWS+30%) speed.
  - Walking over a 10, 20 and 30 cm obstacle.
  - Gait initiation and termination.
  - Deep squatting (DS).
  - Stair ascent (SA) and descent (SD).

M-Tech

ANYBODY™ RESEARCH PROJECT

Modelling

- The AnyBody Modeling System v. 5.3.1.
- New Twente lower extremity model (TLEM) v. 2.0. (Carbone et al, 2015).
- Hill-type muscle models.



Fluit et al. 2014. Prediction of ground reaction forces and moments during various activities of daily living. *J. Biomech*. 47(10), 2321–2329

M-Tech

ANYBODY™ RESEARCH PROJECT

Modelling: scaling

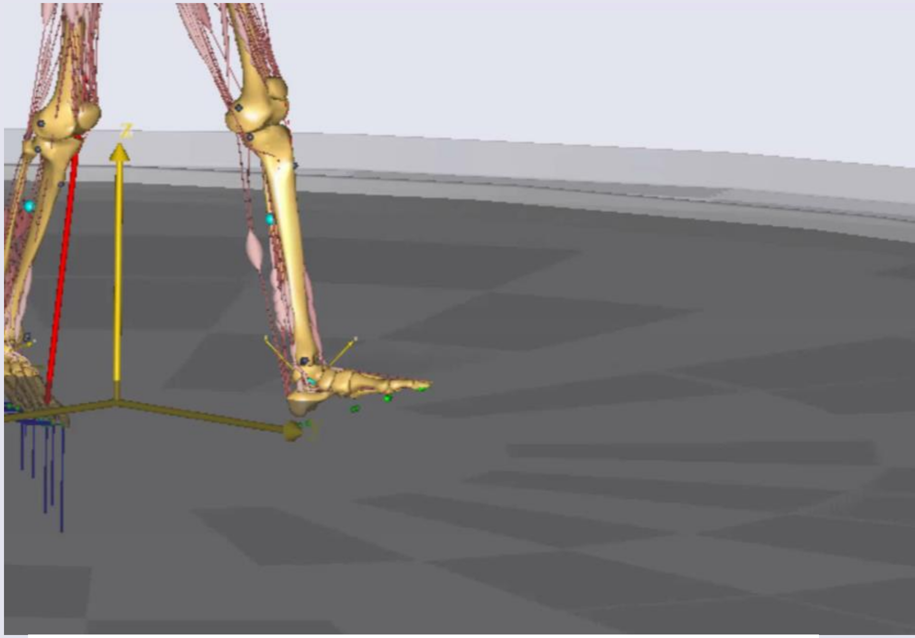
- Segment length and marker location optimisation (Andersen et al. 2010).
- Performed on one gait trial per subject.

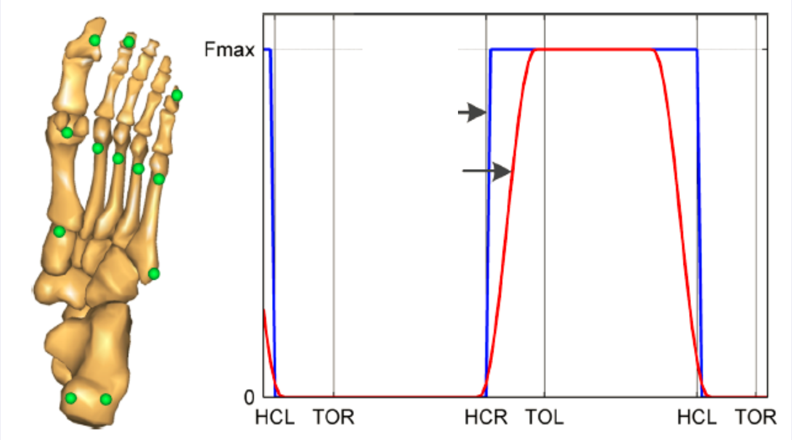
M-Tech

ANYBODY™
RESEARCH PROJECT

Modelling: contact model

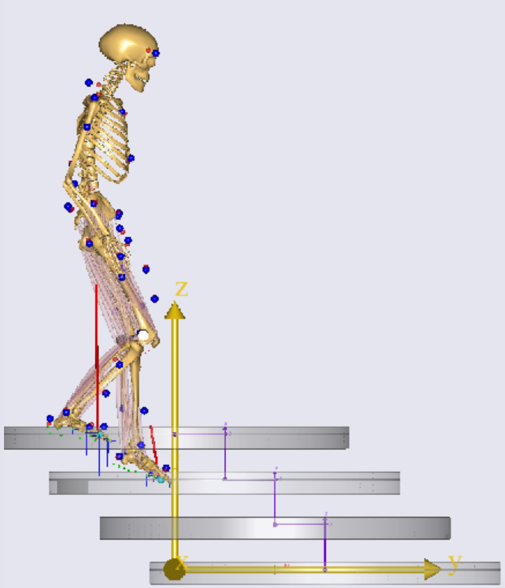
- Coulomb friction model.
- Normal and static friction forces modelled with muscle-like actuators.
- 12 contact points under each foot.
- Ground contact when:
  - Node close to the ground plane.
  - Node velocity small.
- Transitions are smoothed by controlling the strength of the contact ”muscle”.
- Residual ”muscles” on pelvis with low strength.

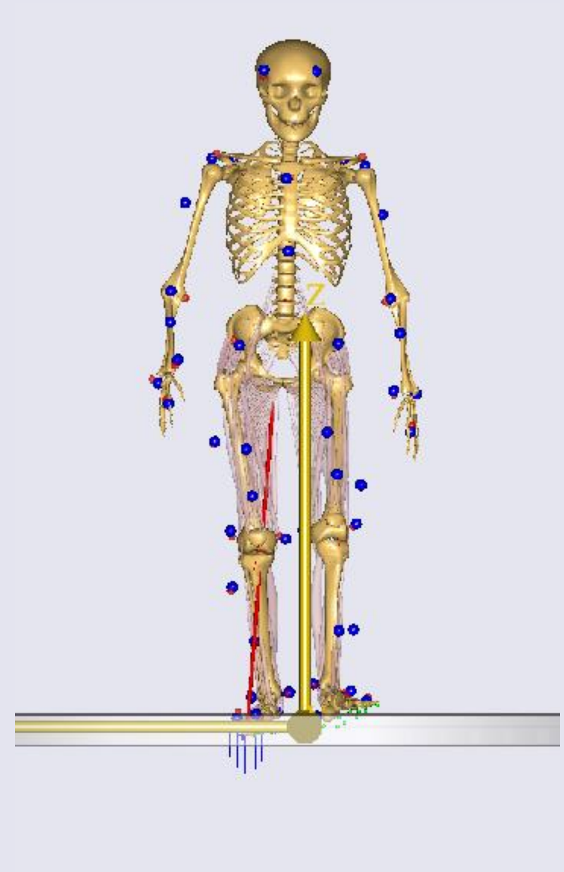




Modelling: inverse dynamics

- Simultaneously computes the muscle, joint and ground reaction forces.
- Masses distributed according to Winter.
- Strength: Length-mass-fat scaling (Rasmussen et al., 2005).
- Recruitment criterion: Sum of muscle activitities cubed.



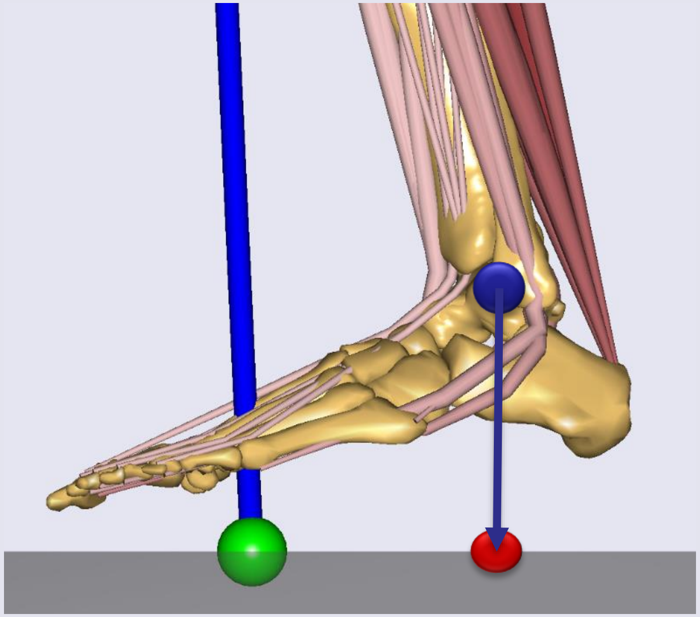


M-Tech

ANYBODY™
RESEARCH PROJECT

Comparisons

- **Variables**
  - GRF&M:
    - Force plate reference frame.
    - Equivalent GRM at the location of the ankle joint center projected onto the force plate.
  - Joint moments.
- **Metrics**
  - Root-mean-square difference (RMSD).
  - Pearson correlation coefficient, ρ.
- **Statistics**
  - Two-tailed Wilcoxon signed rank test.
    - Mean GRF&M.
    - Peak GRF&M.

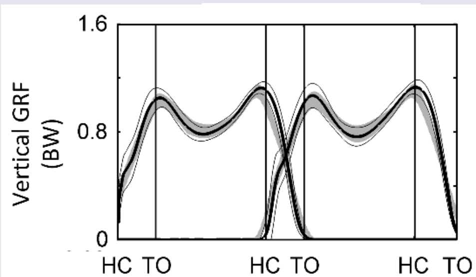


M-Tech

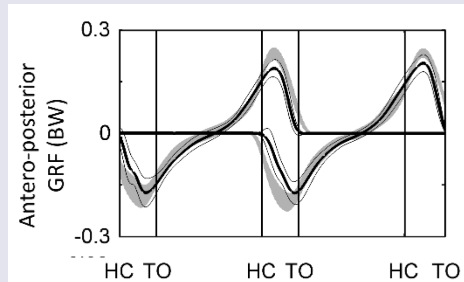
ANYBODY™ RESEARCH PROJECT

CWS results: GRF&M

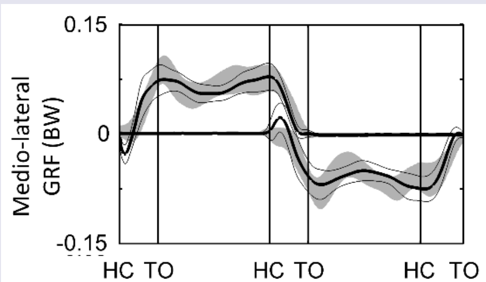
RMSD: 0.08 (0.01) BW
ρ: 0.96



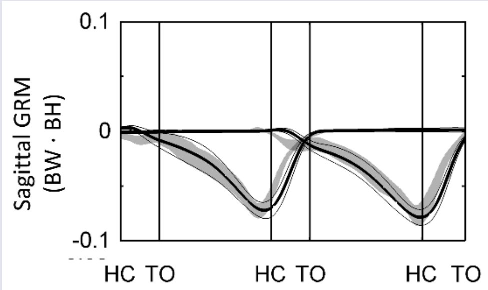
RMSD: 0.04 (0.01) BW
ρ: 0.96



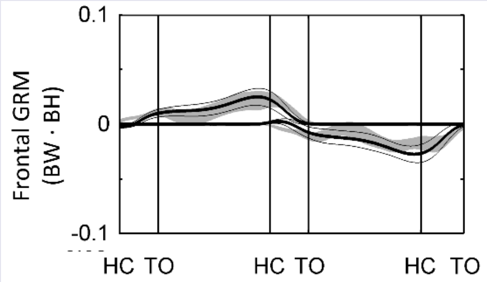
RMSD: 0.02 (0.00) BW
ρ: 0.82



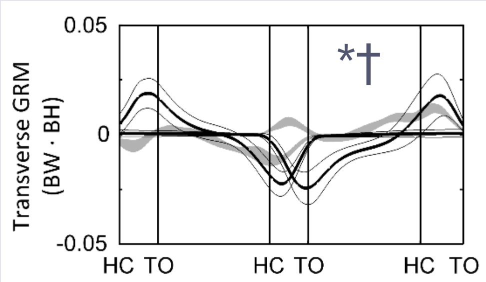
RMSD: 0.02 (0.01) BW
ρ: 0.92



RMSD: 0.01 (0.00) BW
ρ: 0.68



RMSD: 0.02 (0.01) BW
ρ: 0.70



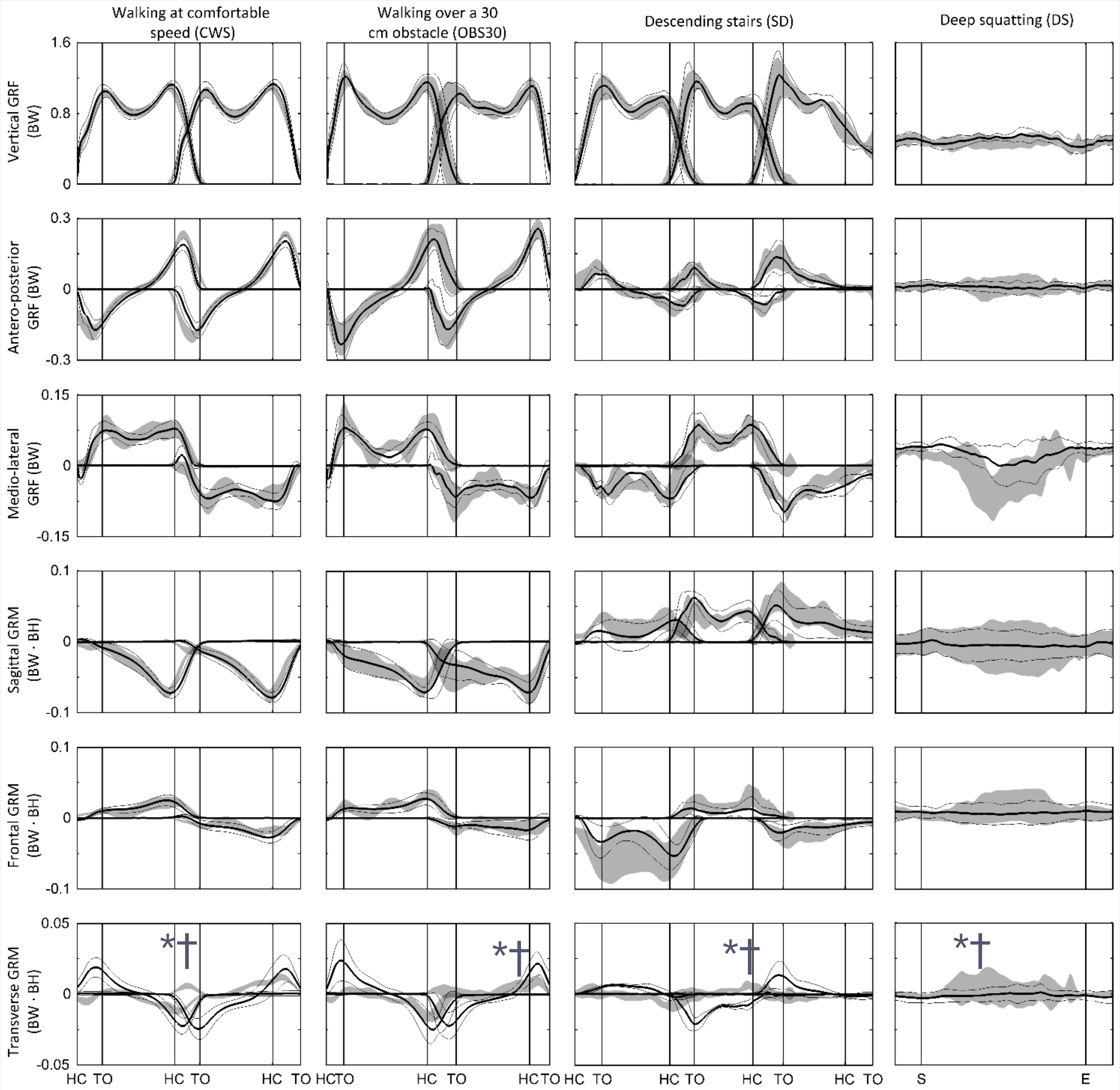
- Black, solid line: mean experimental data.
- Thin lines: ± 1 SD in the experimental data.
- Gray area: predicted mean ± 1 SD.

*: significant difference in mean.
†: significant difference in peak.

M-Tech

ANYBODY™
RESEARCH PROJECT

Results: GRF&M



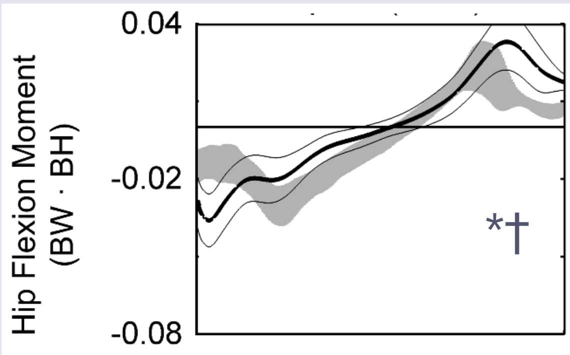
*: Significant difference in mean.
†: Significant difference in peak.
$p < 0.05$

- **Black, solid line**: mean experimental data.
- **Thin lines:** ± 1 SD in the experimental data.
- **Gray area**: predicted mean ± 1 SD.

ANYBODY™ RESEARCH PROJECT

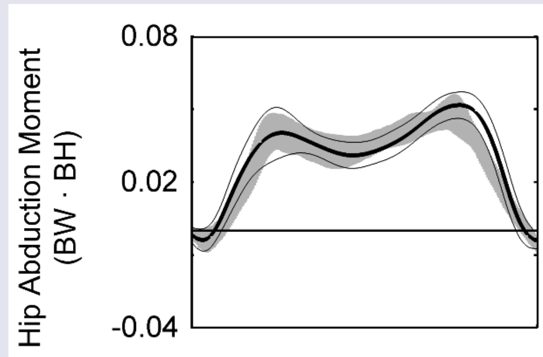
CWS results: Joint moments

ρ: 0.83



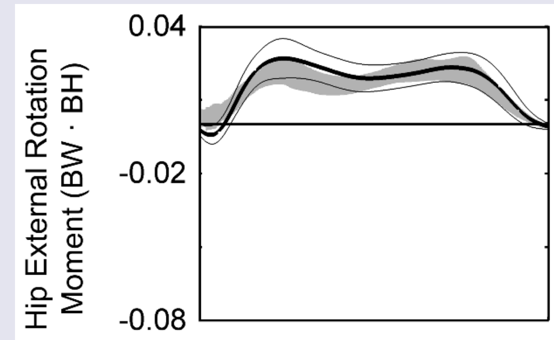
stance phase

ρ: 0.94



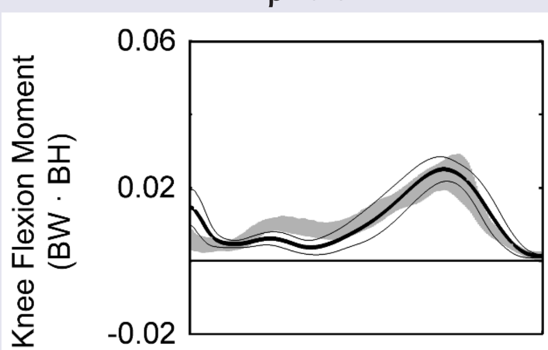
stance phase

ρ: 0.89



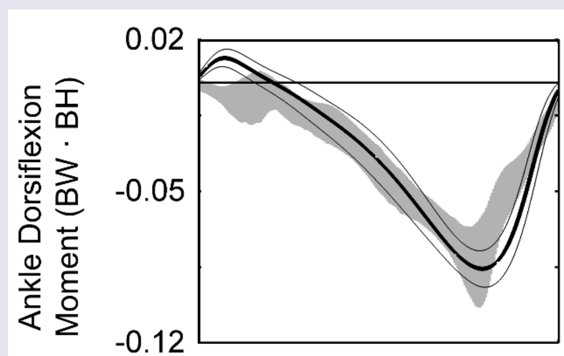
stance phase

ρ: 0.82



stance phase

ρ: 0.93



stance phase

*: significant difference in mean.
†: significant difference in peak.
$p < 0.05$

- Black, solid line: mean experimental data.
- Thin lines: ± 1 SD in the experimental data
- Gray area: predicted mean ± 1 SD

M-Tech

ANYBODY™ RESEARCH PROJECT

Conclusions

- Generally, very good agreements between predicted and measured GRF&Ms were found.

- The prediction was poorest for the transverse GRM.
  - Likely caused by the hinge knee model.

- Potential applications:
  - Predictive models.

  - Measurement systems using inertial measurement units only.

  - Treadmill gait without force plates.

  - To improve dynamic consistency in inverse dynamic simulations.

M-Tech

ANYBODY™ RESEARCH PROJECT

Further reading

- Fluit et al. 2014. Prediction of ground reaction forces and moments during various activities of daily living. *J. Biomech*. 47(10), 2321–2329
- Jung et al. 2014. Ground reaction force estimation using an insole-type pressure mat and joint kinematics during walking, *J Biomech*. 47(11), 2693-2699
- Skals 2015. Prediction of ground reaction forces and moments during sports-related movements, Master's Thesis, Aalborg University, Denmark

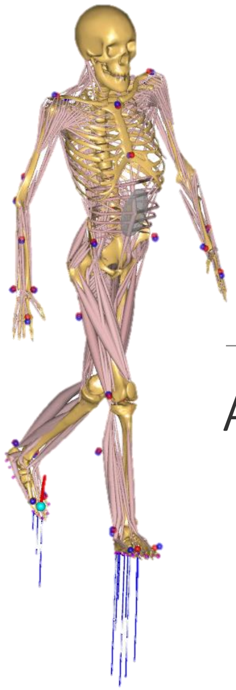
M-Tech

ANYBODY™ RESEARCH PROJECT

Thank you!

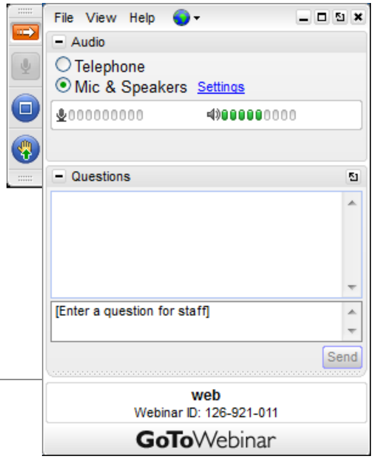
Michael Skipper Andersen, Ph.D.
Associate Professor
Department of Mechanical and Manufacturing Engineering
Aalborg University
msa@m-tech.aau.dk

Any questions for the presenters?
Just ask them now…



Hands on…

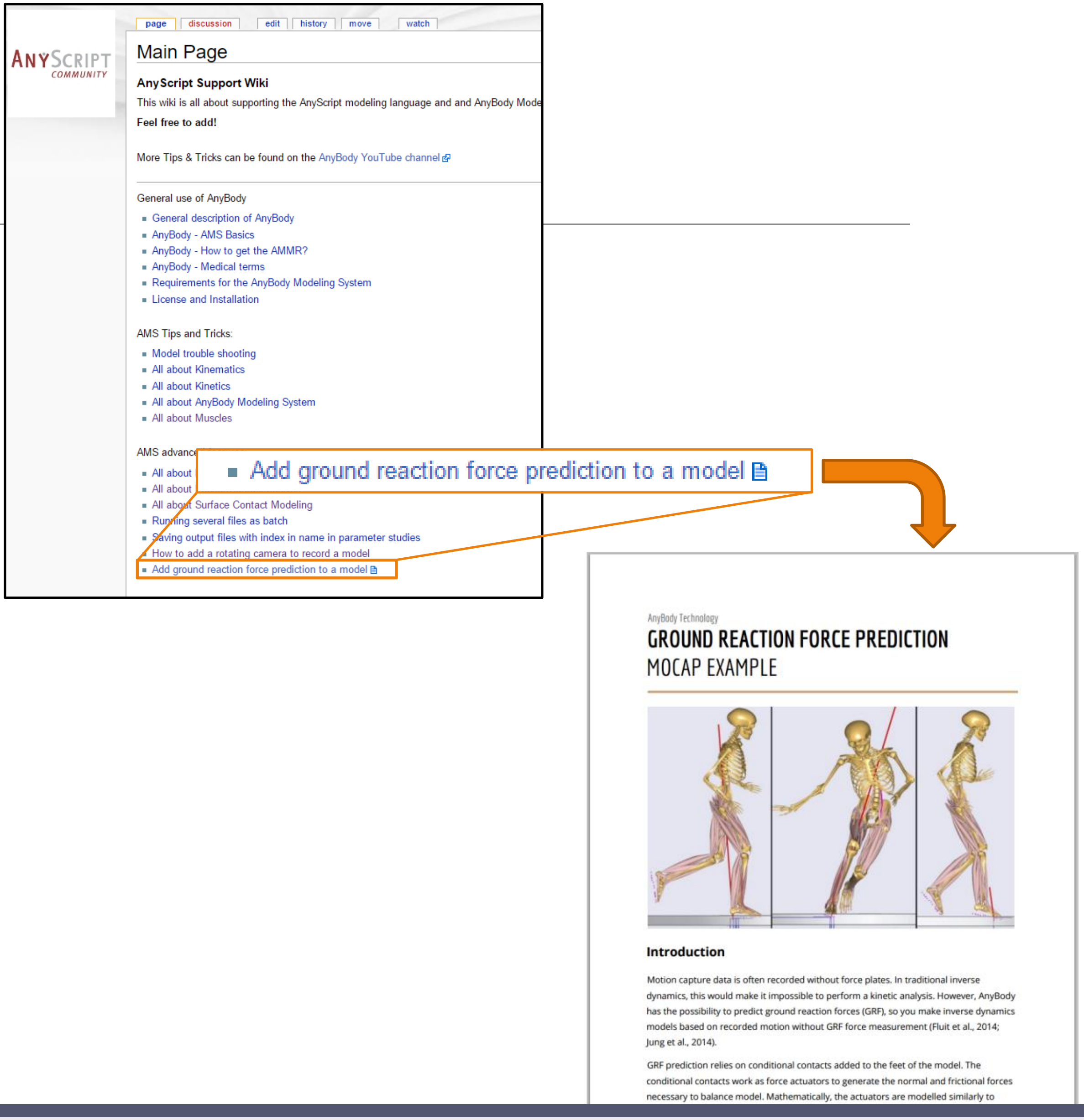
ADDING GRF PREDICTION TO A MOCAP MODEL



Get the code…

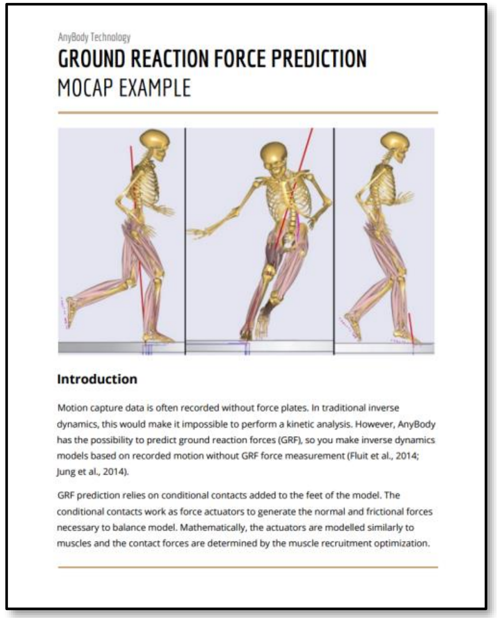
- GRF prediction has always been possible AnyBody for long time, but it has not be easy…
- We have wrapped the code in AnyScript class templates to make it easy to use…
- Available on the wiki.anyscript.org

wiki.anyscript.org



Time for questions:

wiki.anyscript.org



AnyBody Technology

GROUND REACTION FORCE PREDICTION

MOCAP EXAMPLE

Introduction

Motion capture data is often recorded without force plates. In traditional inverse dynamics, this would make it impossible to perform a kinetic analysis. However, AnyBody has the possibility to predict ground reaction forces (GRF), so you make inverse dynamics models based on recorded motion without GRF force measurement (Fluit et al., 2014; Jung et al., 2014).

GRF prediction relies on conditional contacts added to the feet of the model. The conditional contacts work as force actuators to generate the normal and frictional forces necessary to balance model. Mathematically, the actuators are modelled similarly to muscles and the contact forces are determined by the muscle recruitment optimization.

AnyBody events:

- Oct. 27th Webcast:
  - Title: Load Analysis of the hip joint for occupational activities
  - Presenter: Dipl.-Ing. Patrick Varady. Institute of Biomechanics, Trauma Center Murnau and Paracelsus Medical University Salzburg
- Oct. 26th to 30th HFES 2015 (Los Angeles)
  - Send us an email to schedule a meeting: *sales@anybodytech.com*

Visit our website:

- www.anybodytech.com
- For events, dates, publication lists, ...