The webcast will start in a few minutes….

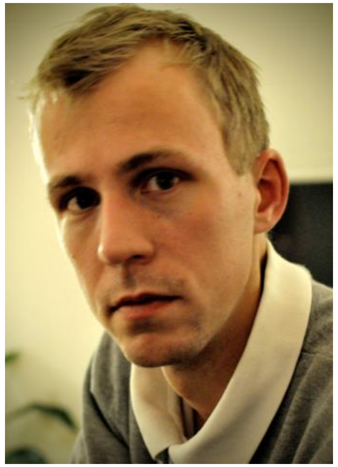
# TLEM*safe* legacy

TOWARDS PERSONALIZATION OF MUSCULOSKELETAL MODELS AND PREDICTION OF FUNCTIONAL OUTCOME

# Outline

- Introduction by the Host
- TLEM*safe* legacy …
  - *Towards personalization of musculoskeletal models and prediction of functional outcome* **by Vincenzo Carbone, University of Twente**
- Final words on TLEM2.0 in AnyBody
- Questions and answers

Vincenzo Carbone
(Presenter)



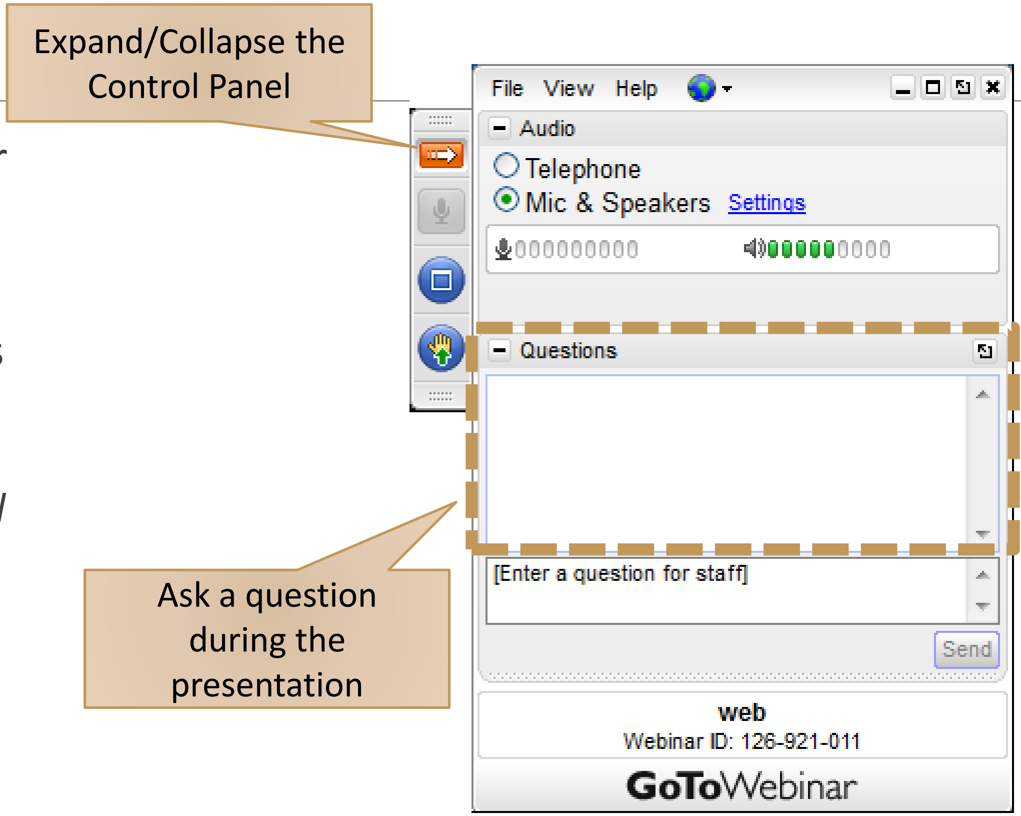
Morten Lund
(Host)

# 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.*



# What is TLEM?
# Twente Lower Extremity Model…

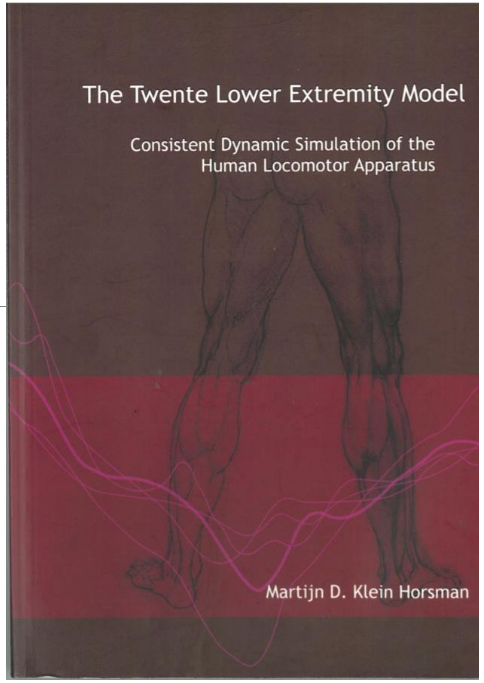
PhD thesis by Martijn Klein Horsman (2007)

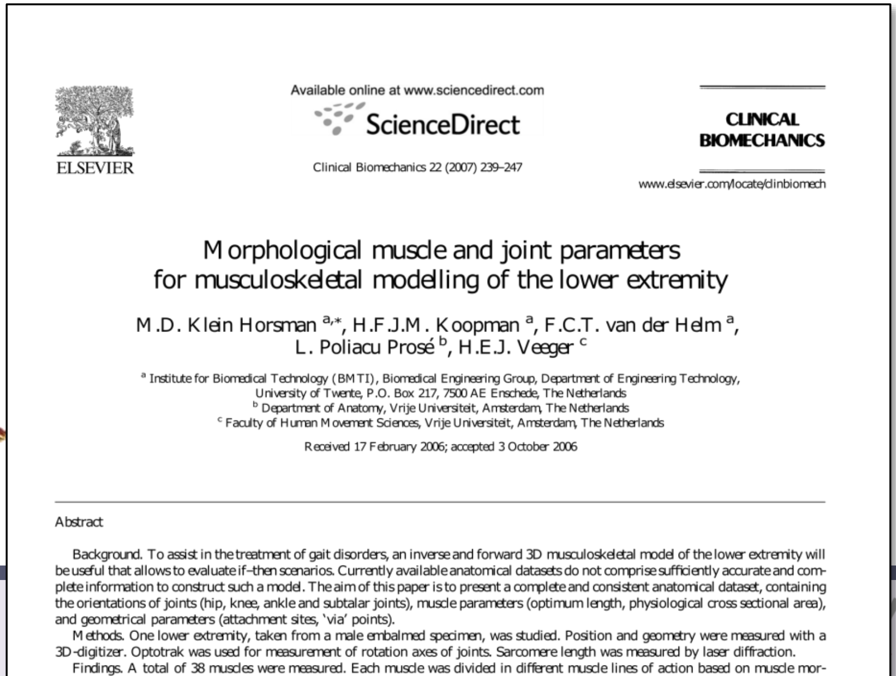
- Comprehensive cadaver study
- Implementation of a computational model
- Validation

Dataset published in *Clin. Biomech.*

- Klein Horsman et al. 2007
- 199 citations (underestimates the real usage of the dataset)

Also an implementation of a leg model in the **A**nyBody **M**anaged **M**odel **R**epository (**AMMR**)

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CLINICAL BIOMECHANICS
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Morphological muscle and joint parameters for musculoskeletal modelling of the lower extremity

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Abstract

Background. To assist in the treatment of gait disorders, an inverse and forward 3D musculoskeletal model of the lower extremity will be useful that allows to evaluate if–then scenarios. Currently available anatomical datasets do not comprise sufficiently accurate and complete information to construct such a model. The aim of this paper is to present a complete and consistent anatomical dataset, containing the orientations of joints (hip, knee, ankle and subtalar joints), muscle parameters (optimum length, physiological cross sectional area), and geometrical parameters (attachment sites, 'via' points).

Methods. One lower extremity, taken from a male embalmed specimen, was studied. Position and geometry were measured with a 3D-digitizer. Optotrak was used for measurement of rotation axes of joints. Sarcomere length was measured by laser diffraction.

Findings. A total of 38 muscles were measured. Each muscle was divided in different muscle lines of action based on muscle mor-

# What is TLEM*safe*?

EU project (grant no: 257860):

- 2010 – 2014
- Coordinated by: Prof. Dr. Ir. Nico Verdonschot

Partners:

- University of Twente
- Radboud University Medical Centre
- Warsaw University of Technology
- Brainlab A.G.
- AnyBody Technology A/S
- Materialise

Continuation of the work of Martijn Klein Horsman

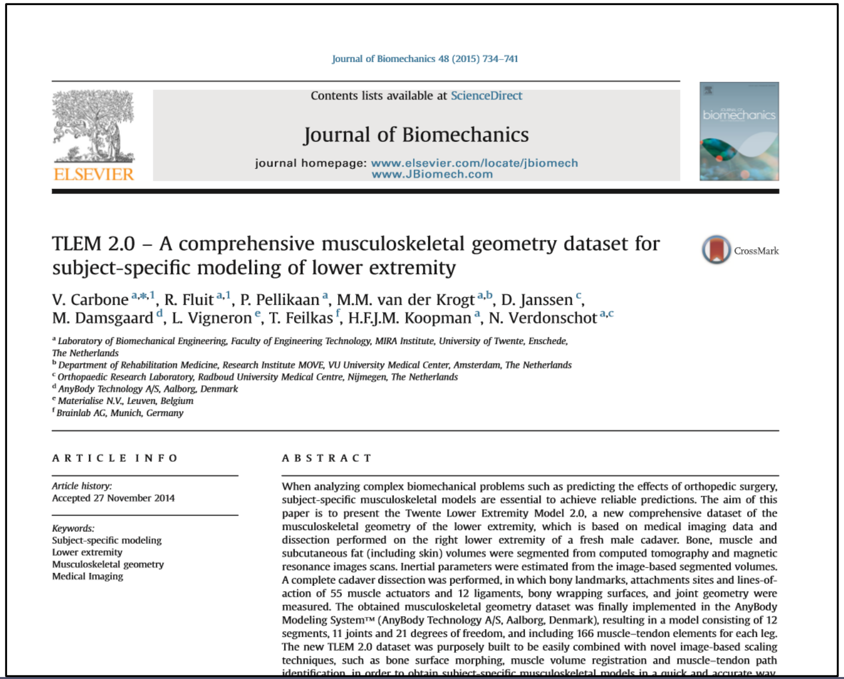
# Vincenzo Carbone

M.Sc. in Mathematical Modeling in Engineering.
Polytechnic University of Turin and the Polytechnic University of Milan.

PhD. Fellow. University of Twente

Project manager for TLEM*safe*

Carbone et al. 2015. *J. Biomech*. 48, 734–741.



Journal of Biomechanics 48 (2015) 734–741

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journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

TLEM 2.0 – A comprehensive musculoskeletal geometry dataset for subject-specific modeling of lower extremity

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[a] Laboratory of Biomechanical Engineering, Faculty of Engineering Technology, MIRA Institute, University of Twente, Enschede, The Netherlands
[b] Department of Rehabilitation Medicine, Research Institute MOVE, VU University Medical Center, Amsterdam, The Netherlands
[c] Orthopaedic Research Laboratory, Radboud University Medical Centre, Nijmegen, The Netherlands
[d] AnyBody Technology A/S, Aalborg, Denmark
[e] Materialise N.V., Leuven, Belgium
[f] Brainlab AG, Munich, Germany

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Lower extremity
Musculoskeletal geometry
Medical Imaging

ABSTRACT

When analyzing complex biomechanical problems such as predicting the effects of orthopedic surgery, subject-specific musculoskeletal models are essential to achieve reliable predictions. The aim of this paper is to present the Twente Lower Extremity Model 2.0, a new comprehensive dataset of the musculoskeletal geometry of the lower extremity, which is based on medical imaging data and dissection performed on the right lower extremity of a fresh male cadaver. Bone, muscle and subcutaneous fat (including skin) volumes were segmented from computed tomography and magnetic resonance images scans. Inertial parameters were estimated from the image-based segmented volumes. A complete cadaver dissection was performed, in which bony landmarks, attachments sites and lines-of-action of 55 muscle actuators and 12 ligaments, bony wrapping surfaces, and joint geometry were measured. The obtained musculoskeletal geometry dataset was finally implemented in the AnyBody Modeling System™ (AnyBody Technology A/S, Aalborg, Denmark), resulting in a model consisting of 12 segments, 11 joints and 21 degrees of freedom, and including 166 muscle–tendon elements for each leg. The new TLEM 2.0 dataset was purposely built to be easily combined with novel image-based scaling techniques, such as bone surface morphing, muscle volume registration and muscle–tendon path identification, in order to obtain subject-specific musculoskeletal models in a quick and accurate way.

The principal researcher in the development and implementation of the new Twente Lower Extremity Model.

One of the main authors of the paper for the TLEM-2.0 model

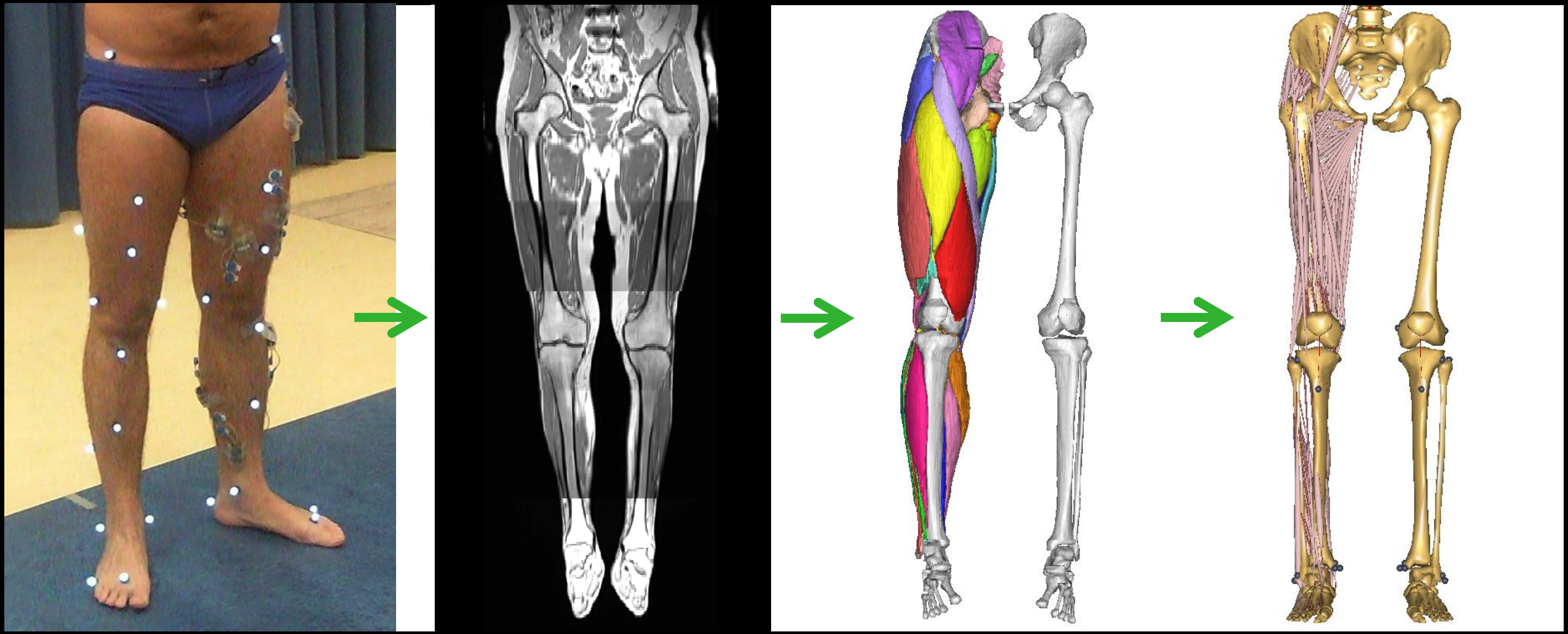
# TLEM*safe* legacy

TOWARDS PERSONALIZATION OF MUSCULOSKELETAL MODELS AND PREDICTION OF FUNCTIONAL OUTCOME

Vincenzo Carbone
PhD Student, M.Sc.
University of Twente

# TLEM*safe* legacy

## Towards personalization of musculoskeletal models and prediction of functional outcome



# Introducing the presenter

- Vincenzo Carbone - v.carbone@utwente.nl
- PhD researcher at University of Twente
- Laboratory of Biomechanical Engineering
- Topic: Subject-specific musculoskeletal models
- TLEM*safe* Project manager


- TLEM*safe* fellows:
  - Sjoerd Kolk
  - Pim Pellikaan
  - René Fluit

# Outline

- TLEM*safe* project
- TLEM 2.0 musculoskeletal dataset
- TLEM*safe* subject-specific modeling workflow
- Subject- and patient-specific models
- Functional outcome after surgery: prediction of kinematics and kinetics

# TLEM*safe*: Patient-specific surgical navigation system

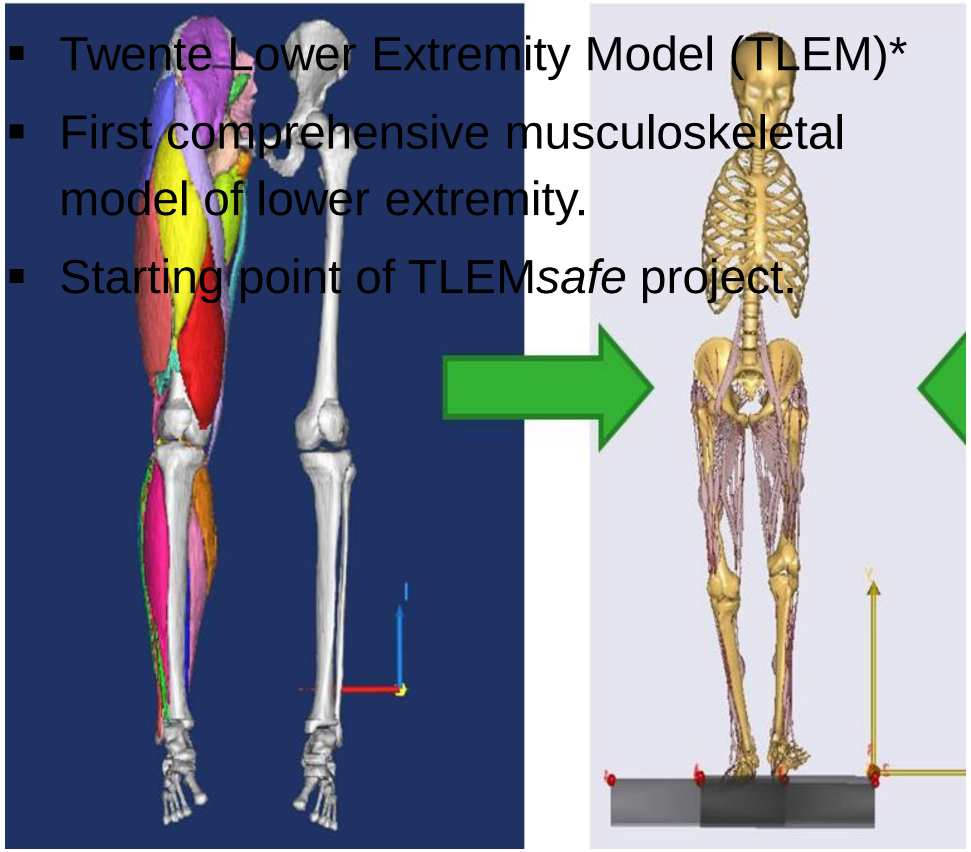
Improve **safety** and **success** of **complex orthopedic surgery**

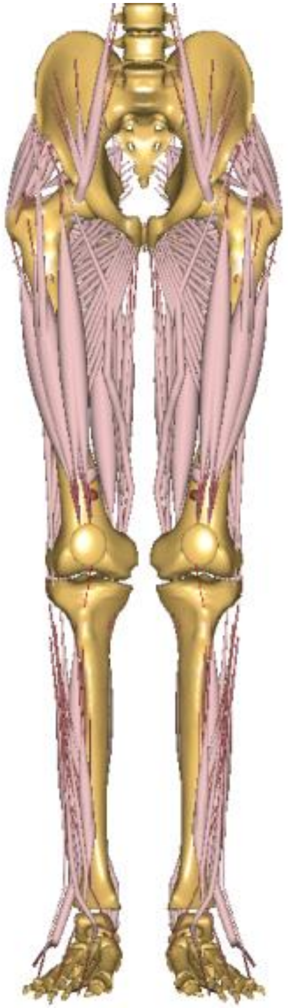

UNIVERSITY OF TWENTE.
Radboudumc university medical center
WARSAW UNIVERSITY OF TECHNOLOGY
ANYBODY TECHNOLOGY
BRAINLAB
Materialise Software
SEVENTH FRAMEWORK PROGRAMME

# TLEM*safe* partners - University of Twente

- Expertise: Biomechanics of human locomotor system.
- Role: Subject-specific models and adaptive capacity of patients.

- Twente Lower Extremity Model (TLEM)*
- First comprehensive musculoskeletal model of lower extremity.
- Starting point of TLEM*safe* project.



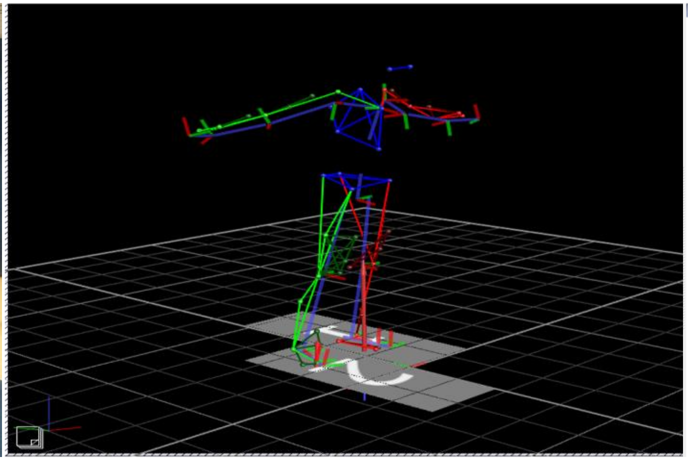
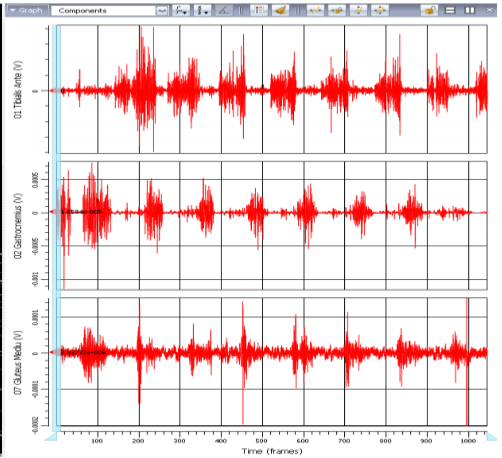


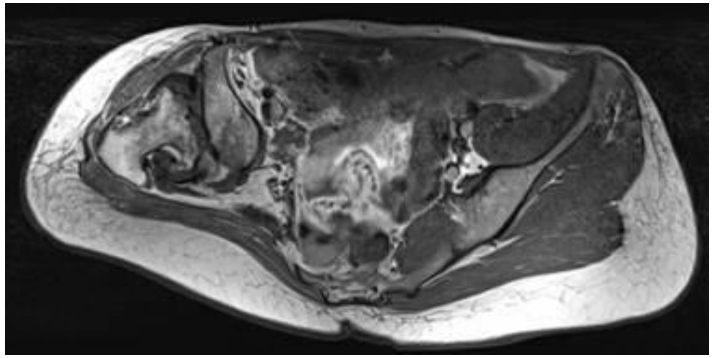
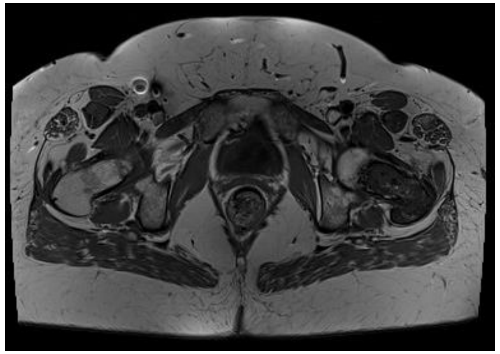
*Klein Horsman et al., 2007, Clin Biomech 22, 239–247.

# TLEM*safe* partners - Radboud UMC

Radboudumc
university medical center

- Expertise: Orthopedic treatment and analysis of posture and gait.
- Role: Collecting functional datasets for healthy subjects, hip-dysplasia* and sarcoma** patients (gait lab measurements, medical images, surgery logs).

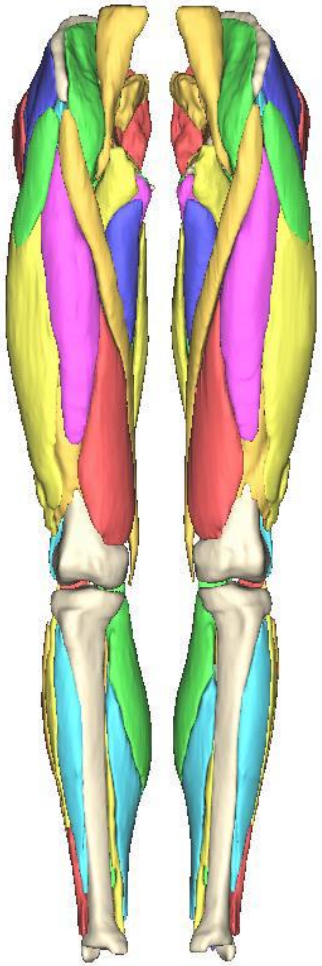
*Kolk S., et al., 2015, *BMC Musculoskeletal Disorders*, **16**:68

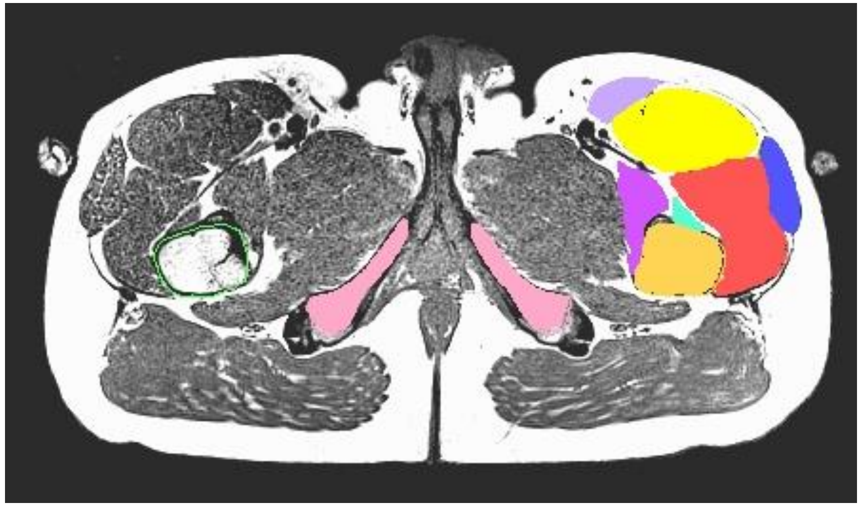
**Kolk S., et al., 2014, Sarcoma, 2014, 436598

# TLEM*safe* partners - Materialise NV

Materialise Software

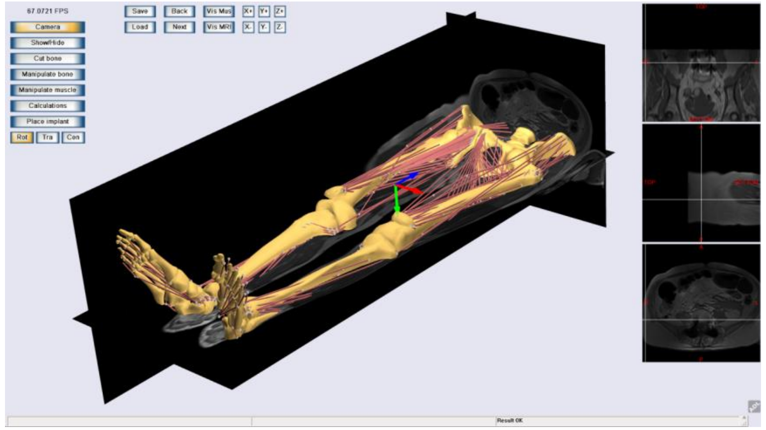
- Expertise: 3D imaging processing and analysis (Mimics® Innovation Suite).
- Role: Extracting personalized parameters from CT and MRI.

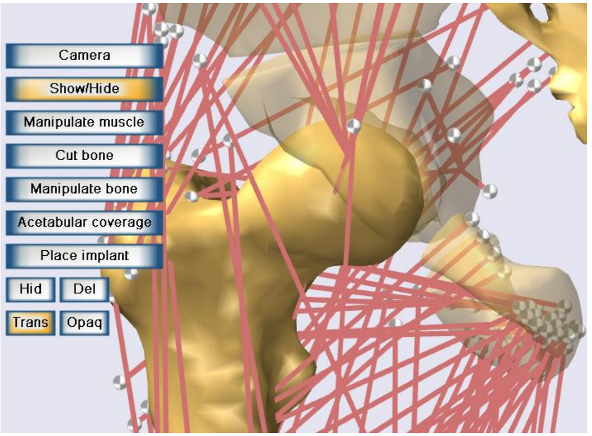


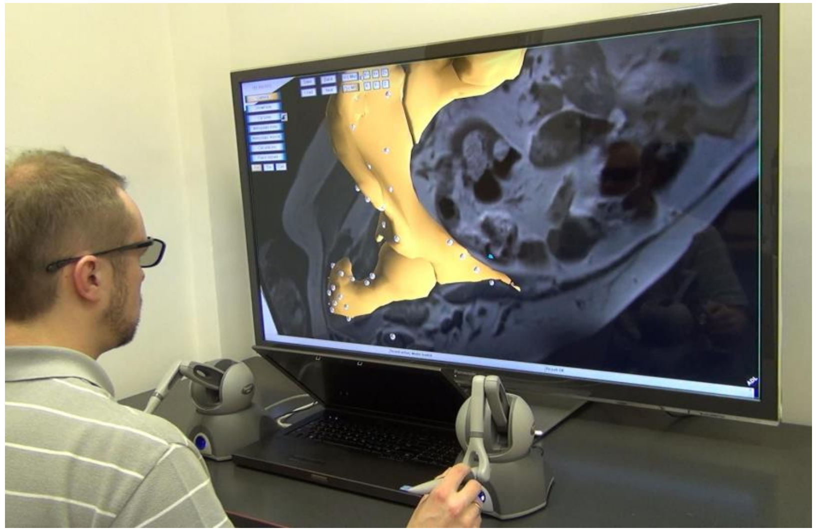


# TLEM*safe* partners - Warsaw University of Technology

- Expertise: Virtual reality applied to medical environments.
- Role: Development of Surgery Planning Environment 3D (SPE3D)*.





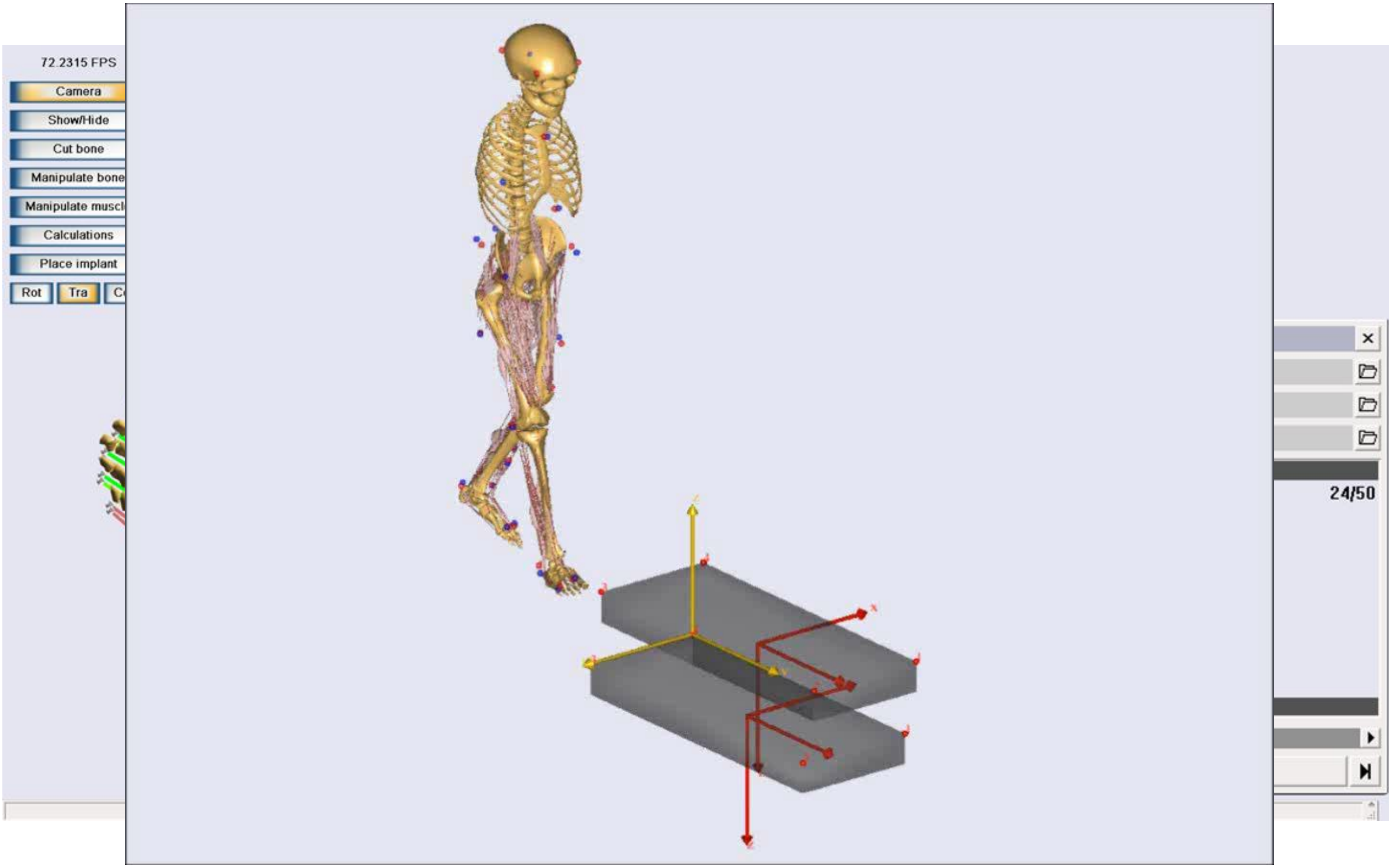



*Witkowski M., et al., 2012, Proc. SPIE 8289, 82890M

*Witkowski M., et al., 2014, Proc. SPIE 9012, 90120E

# TLEM*safe* partners - AnyBody Technology A/S

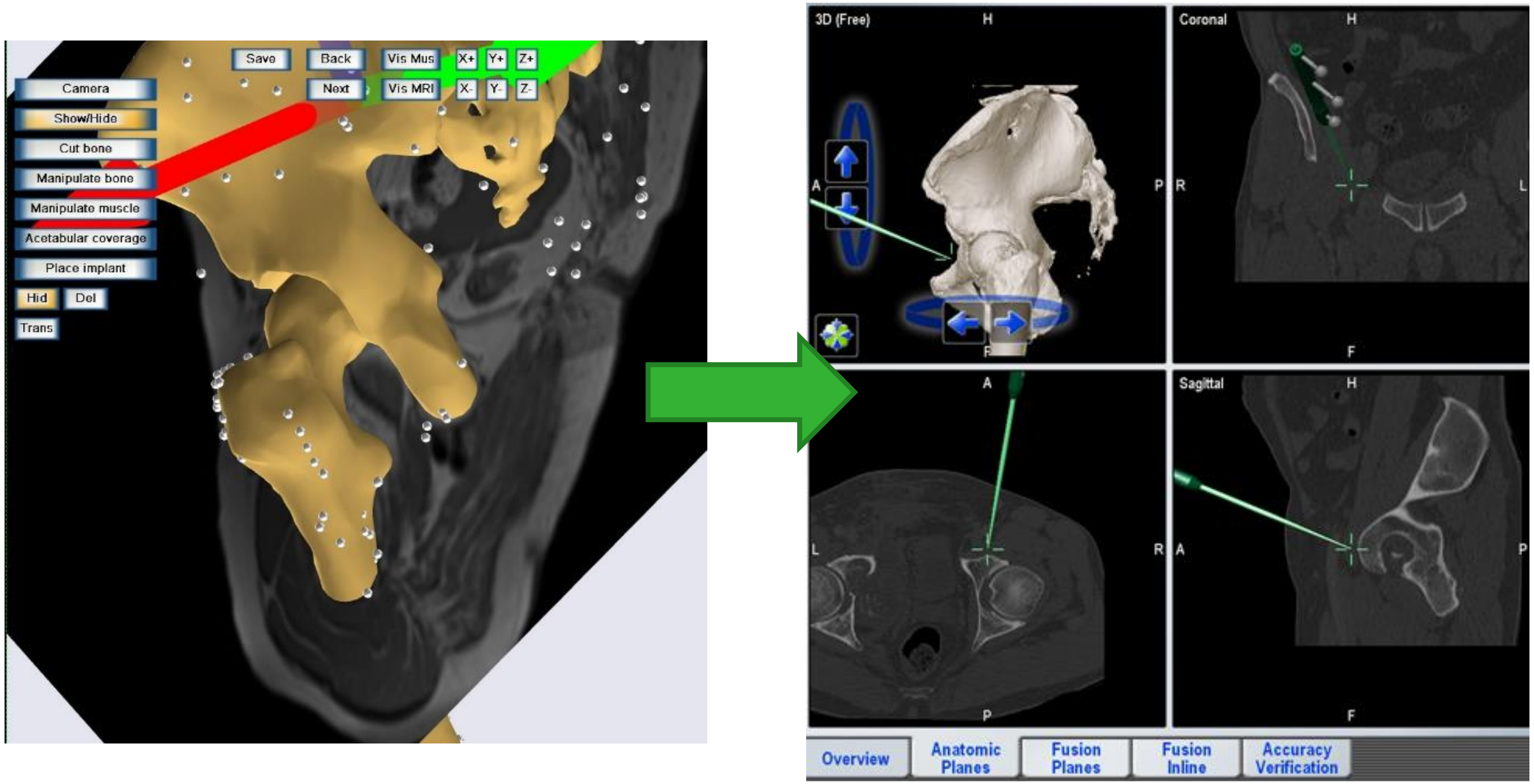
- Expertise: Musculoskeletal simulations (AnyBody Modeling System).
- Role: Linking musculoskeletal model with surgical planning.



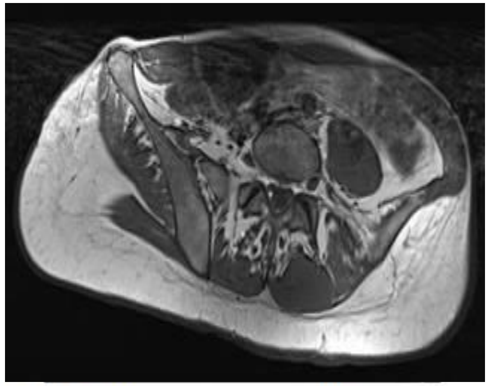
# TLEM*safe* partners – Brainlab AG

BRAINLAB

- Expertise: Surgical navigations systems for orthopedic interventions.
- Role: Integrating virtual surgery into real navigation system.

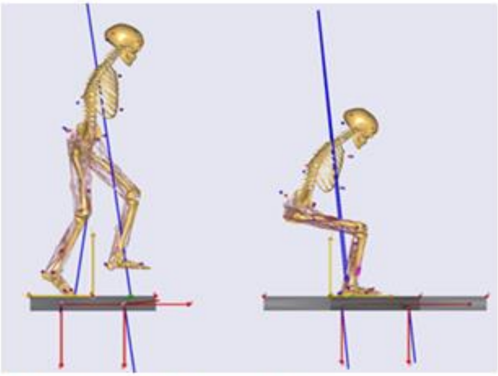


# TLEM*safe* patient workflow

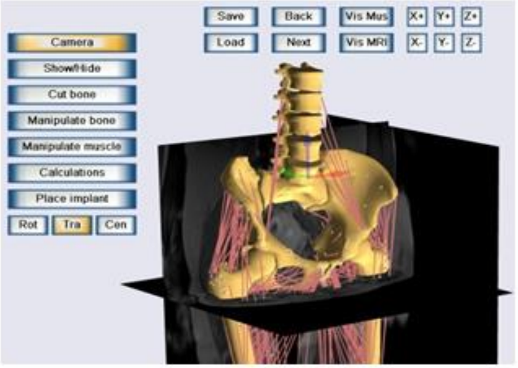


**[1]** Medical images (X-rays and MRI) and functional tests of the patient affected by musculo-skeletal pathology are collected

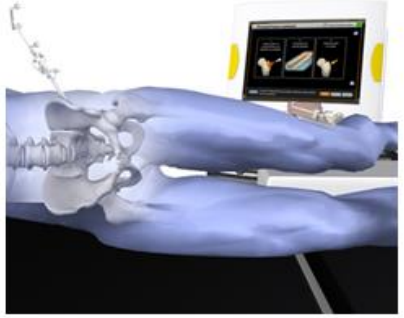
**[2]** Patient-specific data (bony contours, muscle volumes and muscle attachment sites) are extracted from MRI



**[3]** Patient-specific musculo-skeletal model is created to simulate daily living activities (walk, stair climb, sit down)




**[4]** Surgeon uses virtual reality to operate on the patient-specific model and predict the functional effects of the surgery



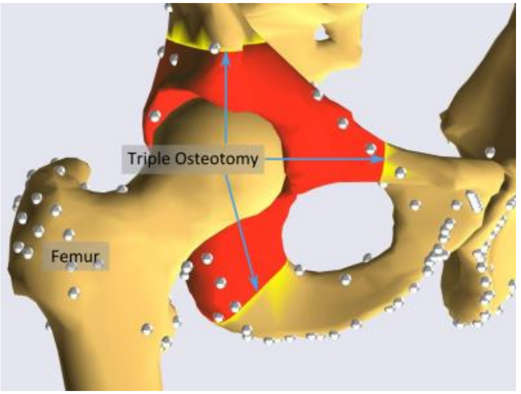
**[5]** Surgical navigation system allows the surgeon to exactly and safely reproduce the selected operative plan

**[6]** Optimal functional result is reached, decreasing risk of complication and improving quality of life for the patient

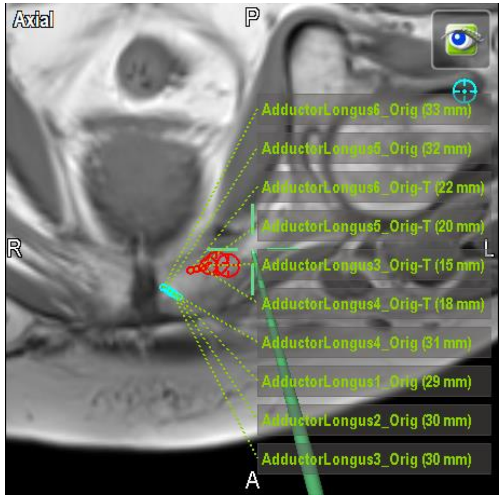
# TLEM*safe* patient workflow

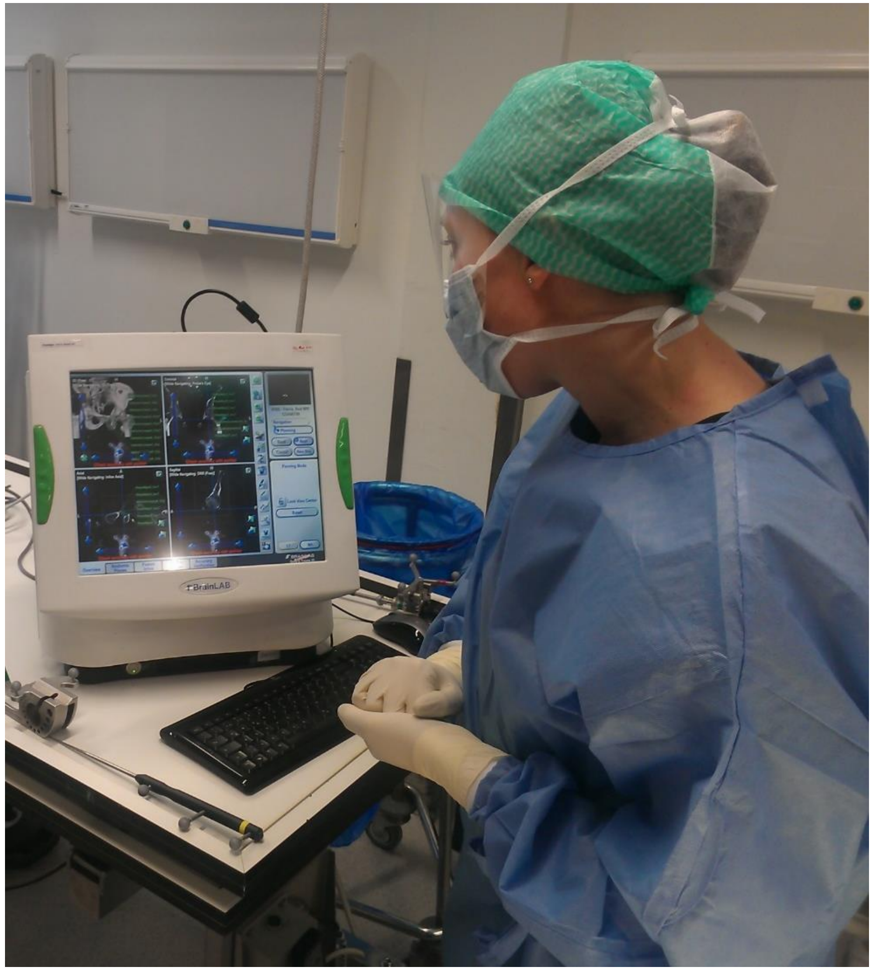
- All steps successfully connected.
- Surgical procedures pre-planned and exactly reproduced on cadaver.

Triple Osteotomy - Pelvis




Muscle Transfer



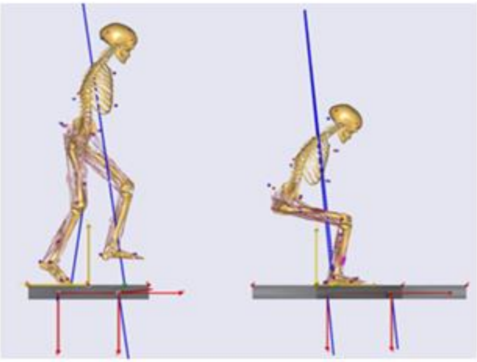



# Role of UT: Personalized models and prediction of outcome

## TLEM*safe* patient workflow

**[1]** Medical images (X-rays and MRI) and functional tests of the patient affected by musculo-skeletal pathology are collected

**[2]** Patient-specific data (bony contours, muscle volumes and muscle attachment sites) are extracted from MRI



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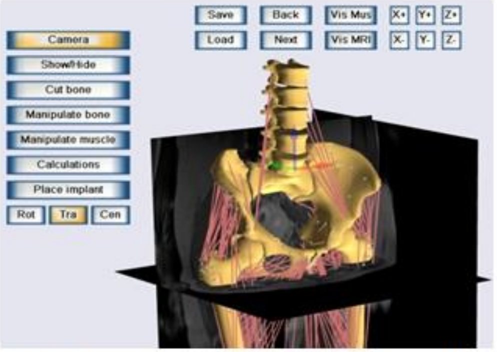
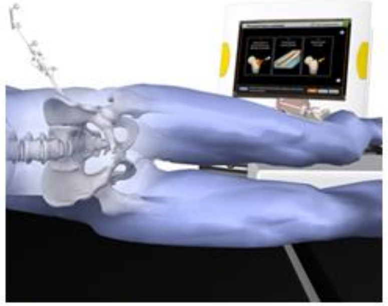



**[4]** Surgeon uses virtual reality to operate on the patient-specific model and predict the functional effects of the surgery



**[5]** Surgical navigation system allows the surgeon to exactly and safely reproduce the selected operative plan

**[6]** Optimal functional result is reached, decreasing risk of complication and improving quality of life for the patient

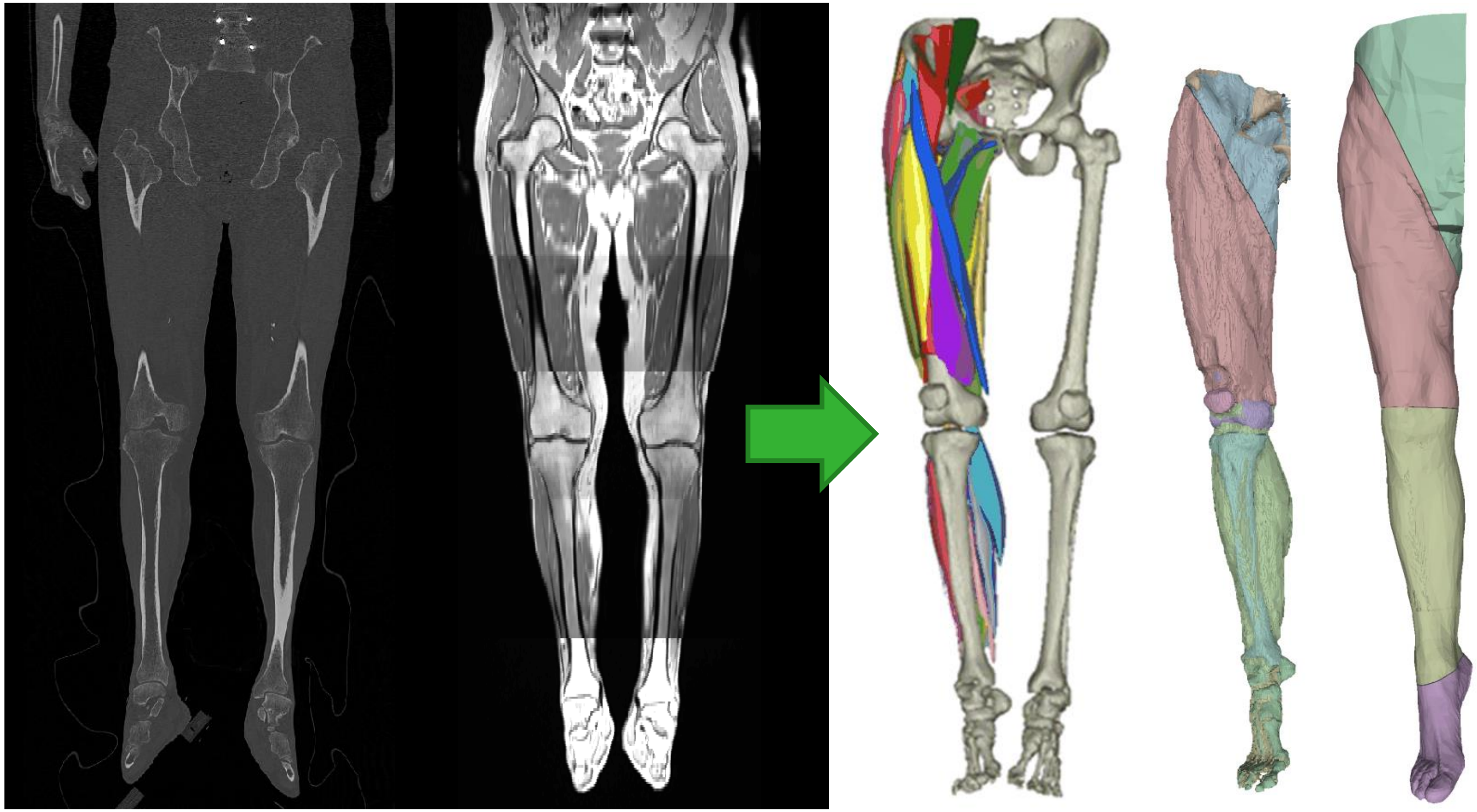
# Personalization of musculoskeletal models

- Patient-specific models are necessary to predict surgical outcome.
- Goal: Model "template" to be combined with image-based scaling techniques and morphed into personalized models.
- Problem: High quality MRI scan of TLEM specimen not available!!!
- We needed an updated version of Twente Lower Extremity Model.

# Twente Lower Extremity Model 2.0

New **complete** and **consistent** dataset of musculoskeletal geometry:

- **CT** and **MRI scans**, segmented **bone**, **muscle** and **fat volumes**.

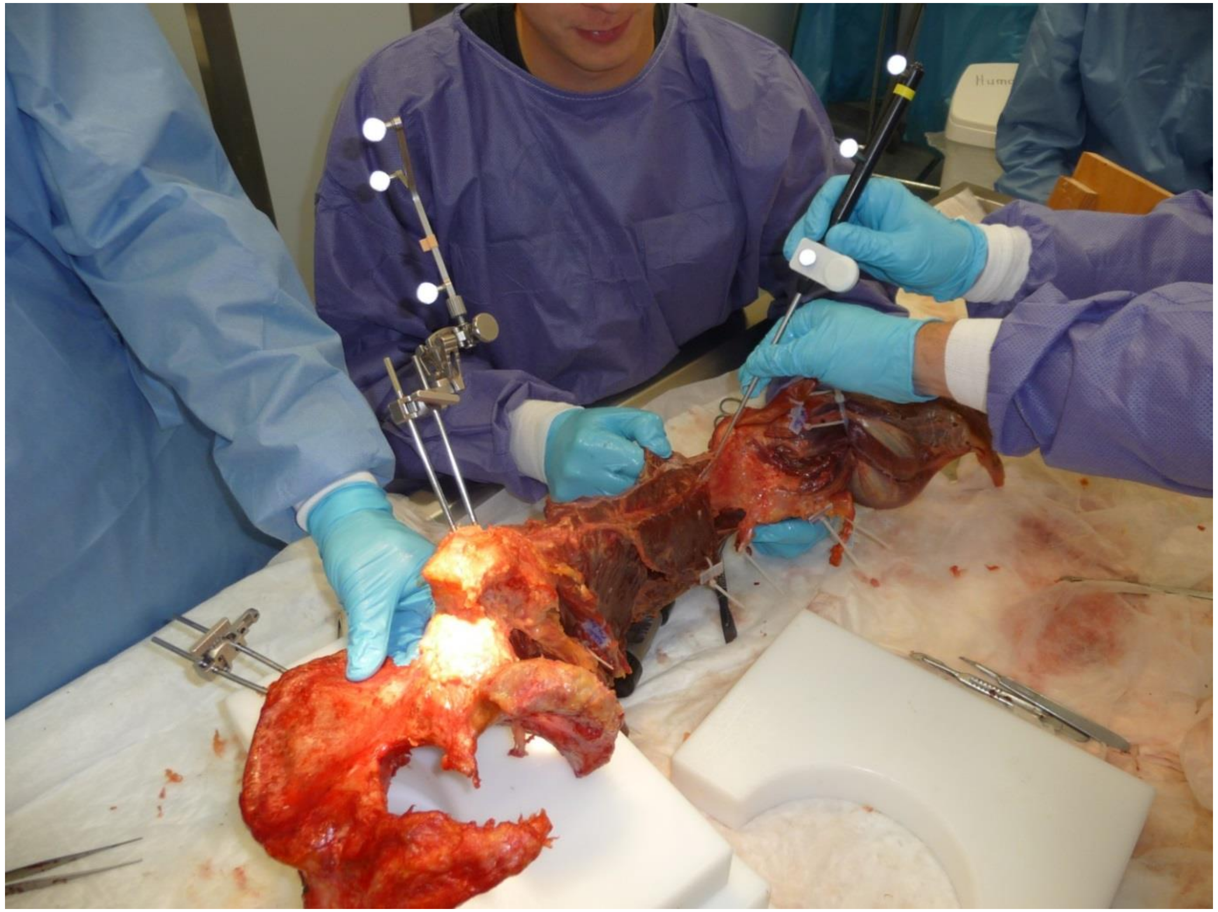


***Carbone, V., Fluit R., et al., 2015, J Biomech 48, 734-741.**

# Twente Lower Extremity Model 2.0

New **complete** and **consistent** dataset of musculoskeletal geometry:

- **Muscle attachment sites, lines-of-action** from cadaver measurement.



***Carbone, V., Fluit R., et al., 2015, J Biomech 48, 734-741.

# Twente Lower Extremity Model 2.0

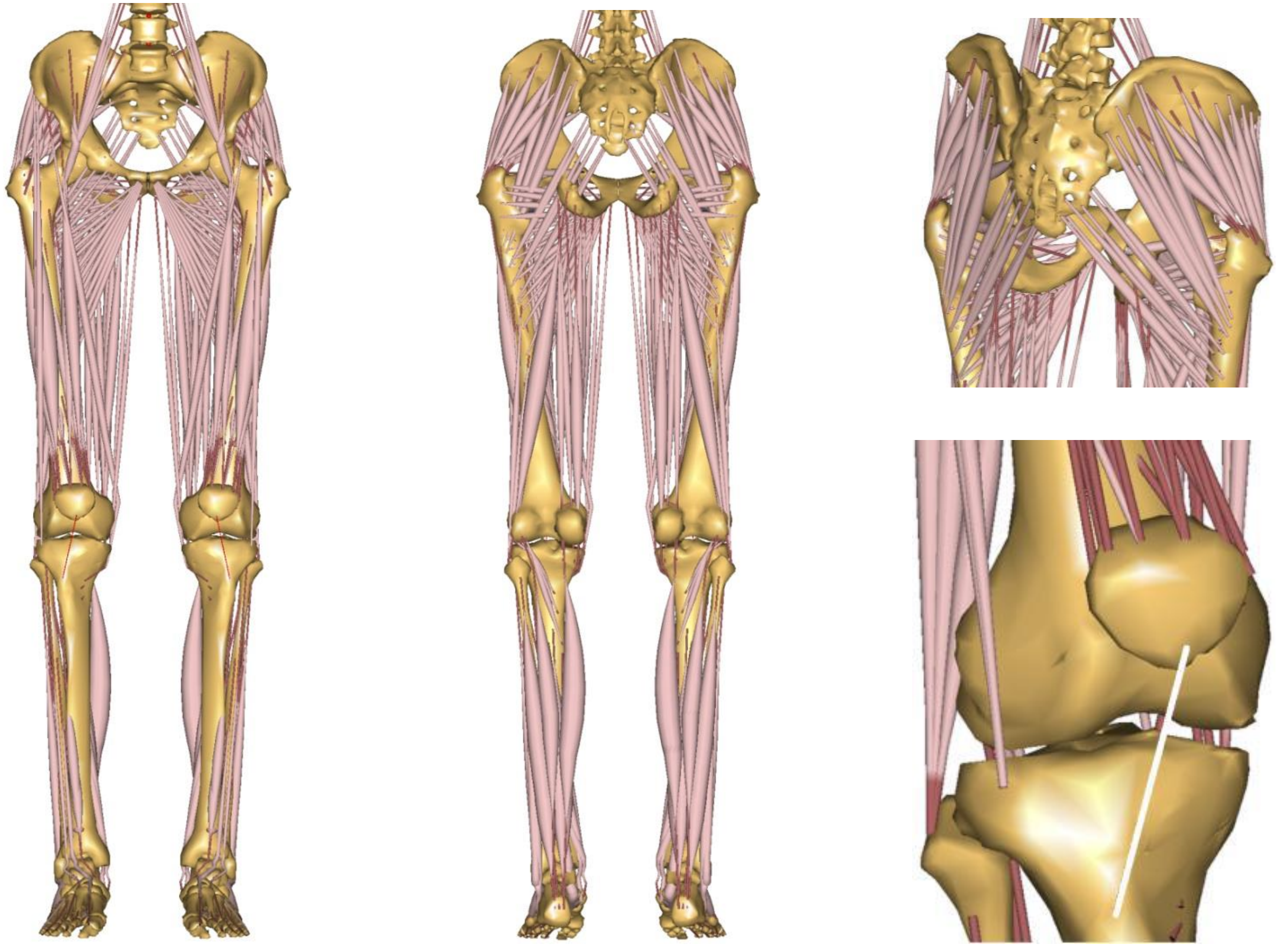
New **complete** and **consistent** dataset of musculoskeletal geometry:

- **Joint geometry** from cadaver measurement.

*****Carbone, V., Fluit R., et al., 2015, J Biomech 48, 734-741.

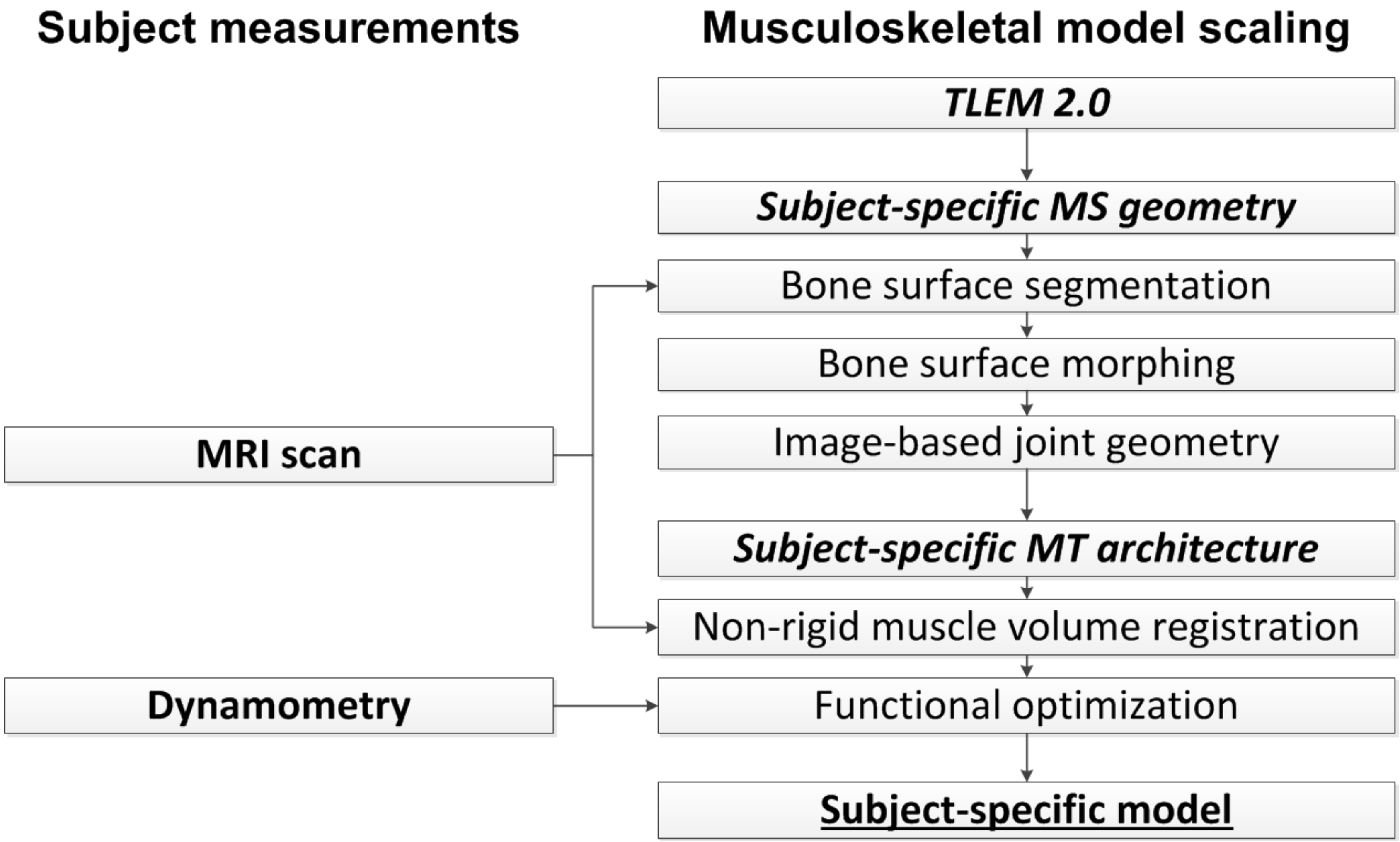
# Twente Lower Extremity Model 2.0

- TLEM 2.0 combined with muscle-tendon parameters from original TLEM.
- New musculoskeletal model implemented in AnyBody Modeling System.



*Carbone, V., Fluit R., et al., 2015, J Biomech 48, 734-741.

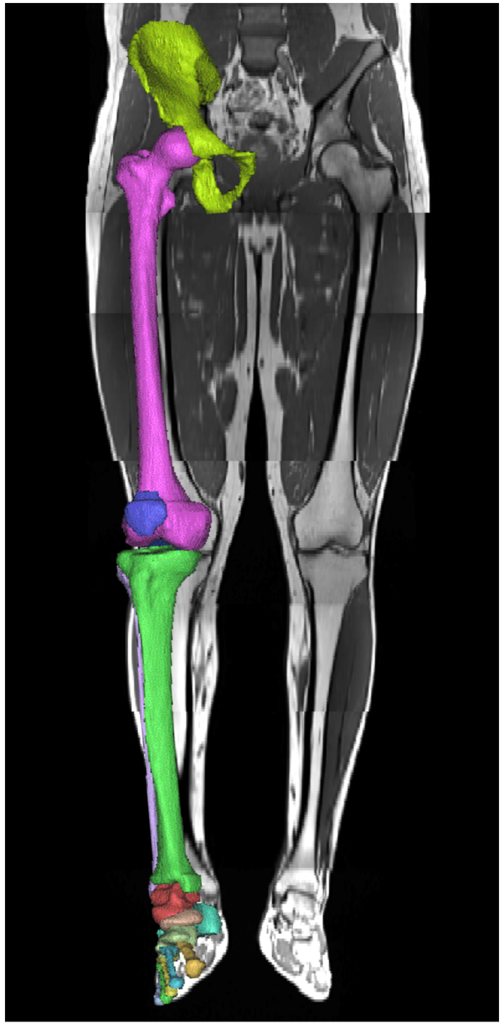
# TLEM*safe* subject-specific modeling workflow




- Subject-specific models created semi-automatically in 1 or 2 days, depending on the quality of MRI.

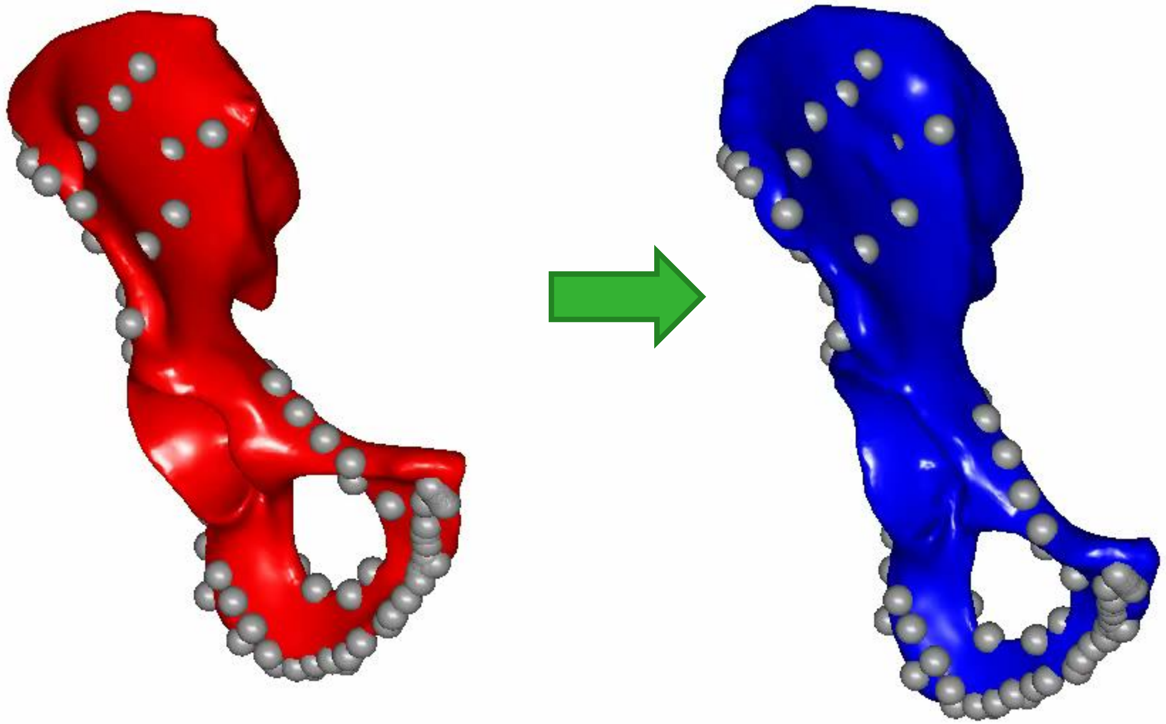
# Subject-specific musculoskeletal geometry

- **Bone surfaces** segmented from MRI.



# Subject-specific musculoskeletal geometry

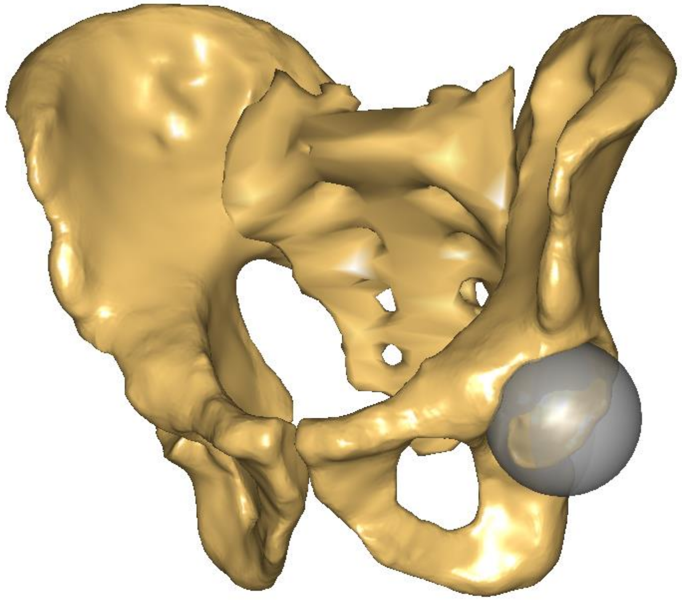
- Automatic morphing from TLEM 2.0 to subject-specific bones.
- **MT attachments** sites follow the morphed bone surface*.

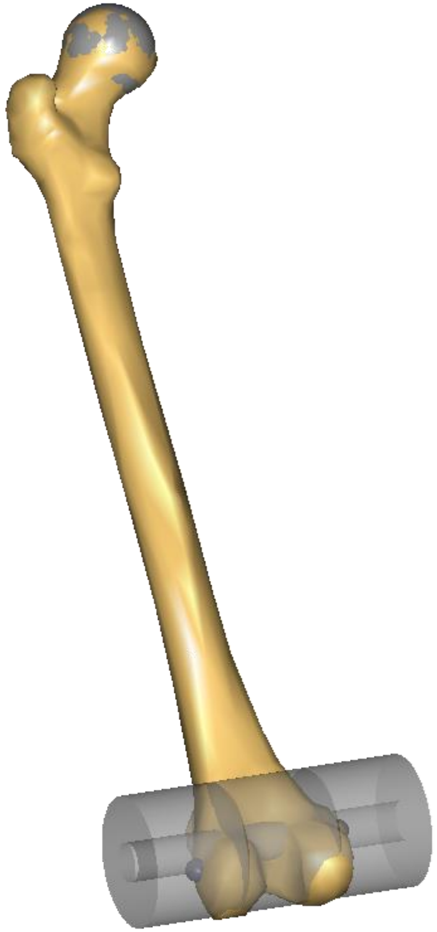


*Pellikaan P., et al., 2014, Journal of Biomechanics, Volume 47, Issue 5, 1144-1150

# Subject-specific musculoskeletal geometry

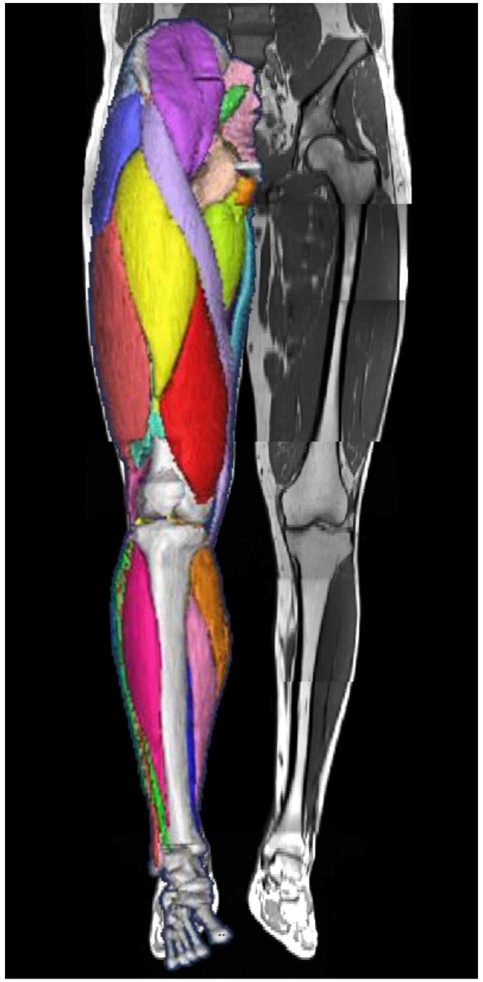
- **Hip joint** based on the sphere that best fit acetabulum and head of femur.
- **Knee joint** axis estimated from the cylinder that best fit the femoral condyles.





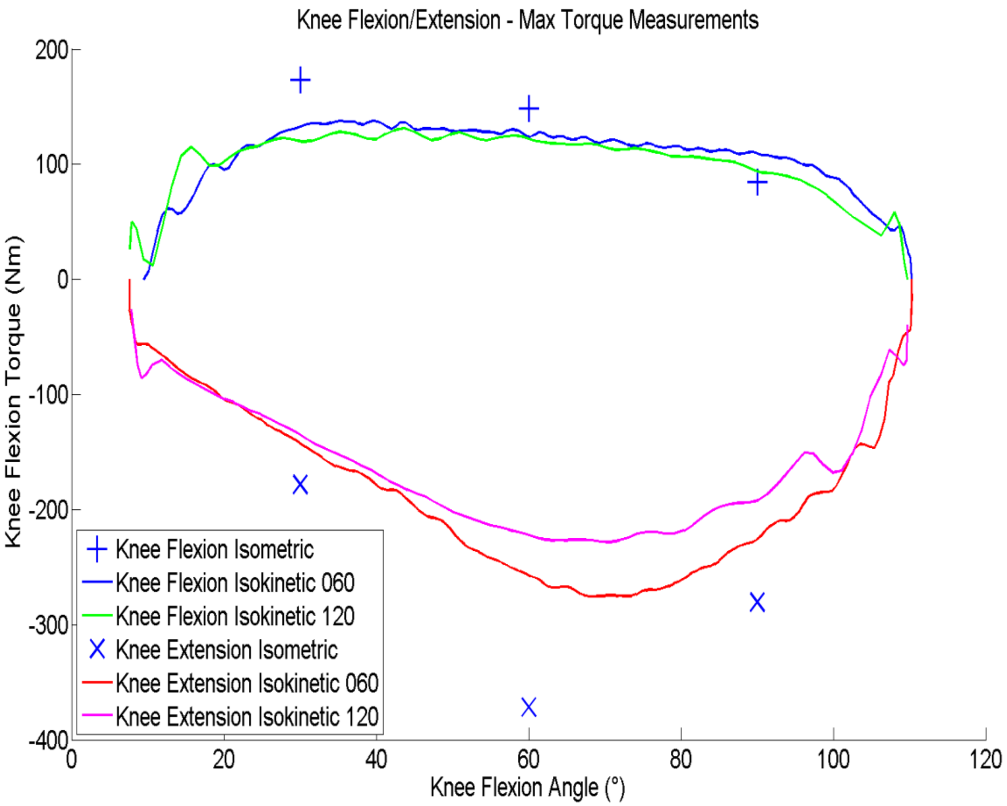
# Subject-specific muscle-tendon architecture

- Non-rigid registration of **muscle volumes** from TLEM 2.0 to subject's MRI.
- **Maximal isometric muscle force** proportional to muscle volume.



# Subject-specific muscle-tendon architecture

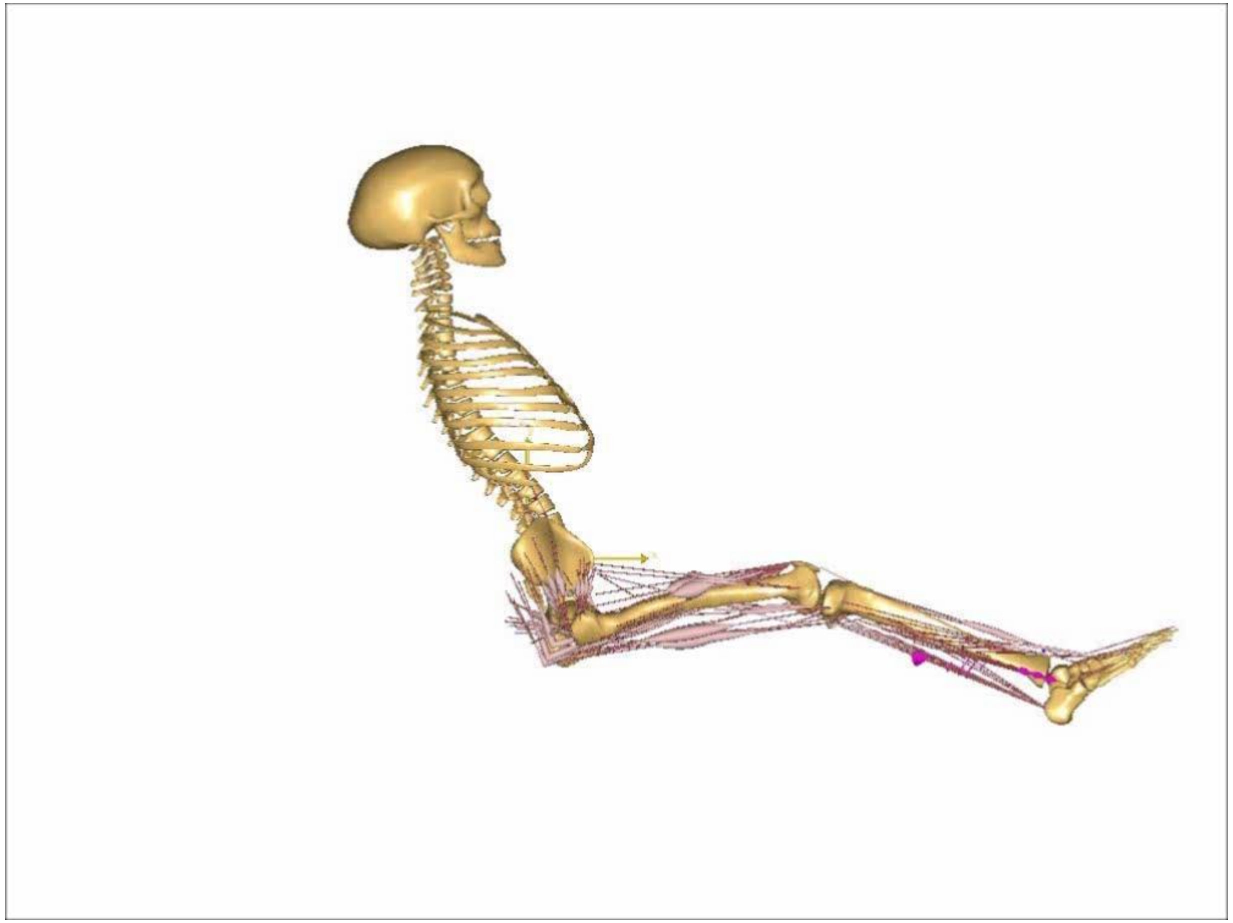
- Functional scaling of **tendon slack length** and **nominal muscle fiber length** to reflect subject-specific force generating characteristics.



# Subject-specific muscle-tendon architecture

- Functional scaling of **tendon slack length** and **nominal muscle fiber length** to reflect subject-specific force generating characteristics.

**Optimization problem:** $min\, J\left(L^0_{T_i}, \overline{L_f}_i, F^M_{0\,i}\right) = \int_0^T |\bar{a}_t - 1|\, dt$



# Healthy subjects-specific models

- Ten subject-specific models created using TLEM*safe* modeling workflow.

# Healthy subjects-specific models

- Differences between musculoskeletal geometry of subject-specific models and linearly scaled models (based on optical markers):

| | Segment size (mm) | | |
|---|---|---|---|
| | **mean** | std | max |
| **Pelvis Width** | **11.03** | 7.32 | 27.54 |
| **Pelvis Depth** | **12.49** | 13.07 | 44.66 |
| **Femur Length** | **7.93** | 4.41 | 15.12 |
| **Tibia Lenght** | **8.32** | 7.05 | 19.89 |

| | Joint position (mm) | | |
|---|---|---|---|
| | **mean** | std | max |
| **Hip Joint center** | **24.90** | 7.88 | 34.60 |
| **Knee Joint center** | **18.99** | 5.08 | 27.63 |

| | Joint direction (°) | | |
|---|---|---|---|
| | **mean** | std | max |
| **Knee Joint angle** | **10.99** | 7.86 | 27.79 |
| **Knee varus/valgus angle** | **5.46** | 3.08 | 11.73 |

| Most sensitive MT attachment sites* | | |
|---|---|---|
| **MT attachment site** | **Segment** | **mean (mm)** |
| **Gluteus Medius Anterior** | Femur | **25.06** |
| **Gluteus Minimus Mid** | Femur | **23.30** |
| **Gluteus Minimus Anterior** | Femur | **23.18** |
| **Biceps Femoris** | Tibia | **22.98** |
| **Gluteus Medius Posterior** | Femur | **22.58** |
| **Gluteus Minimus Posterior** | Femur | **22.33** |
| **Piriformis** | Femur | **21.22** |
| **Gluteus Maximus Inferior** | Pelvis | **20.74** |

***Carbone V., 2012, Journal of Biomechanics, Volume 45, Issue 14, 21 Pages 2476-2480

# Healthy subjects-specific models

- Differences between muscle-tendon architecture of subject-specific models and linearly scaled models (based on size and weight):

| | Muscle-tendon parameters | | |
|---|---|---|---|
| | mean | std | max |
| **Maximal Isometric Muscle Force** | 29.78% | 21.36% | 103.59% |
| **Tendon Slack Length** | 9.99% | 11.14% | 66.42% |
| **Nominal Muscle Fiber Length** | 8.65% | 9.06% | 41.11% |

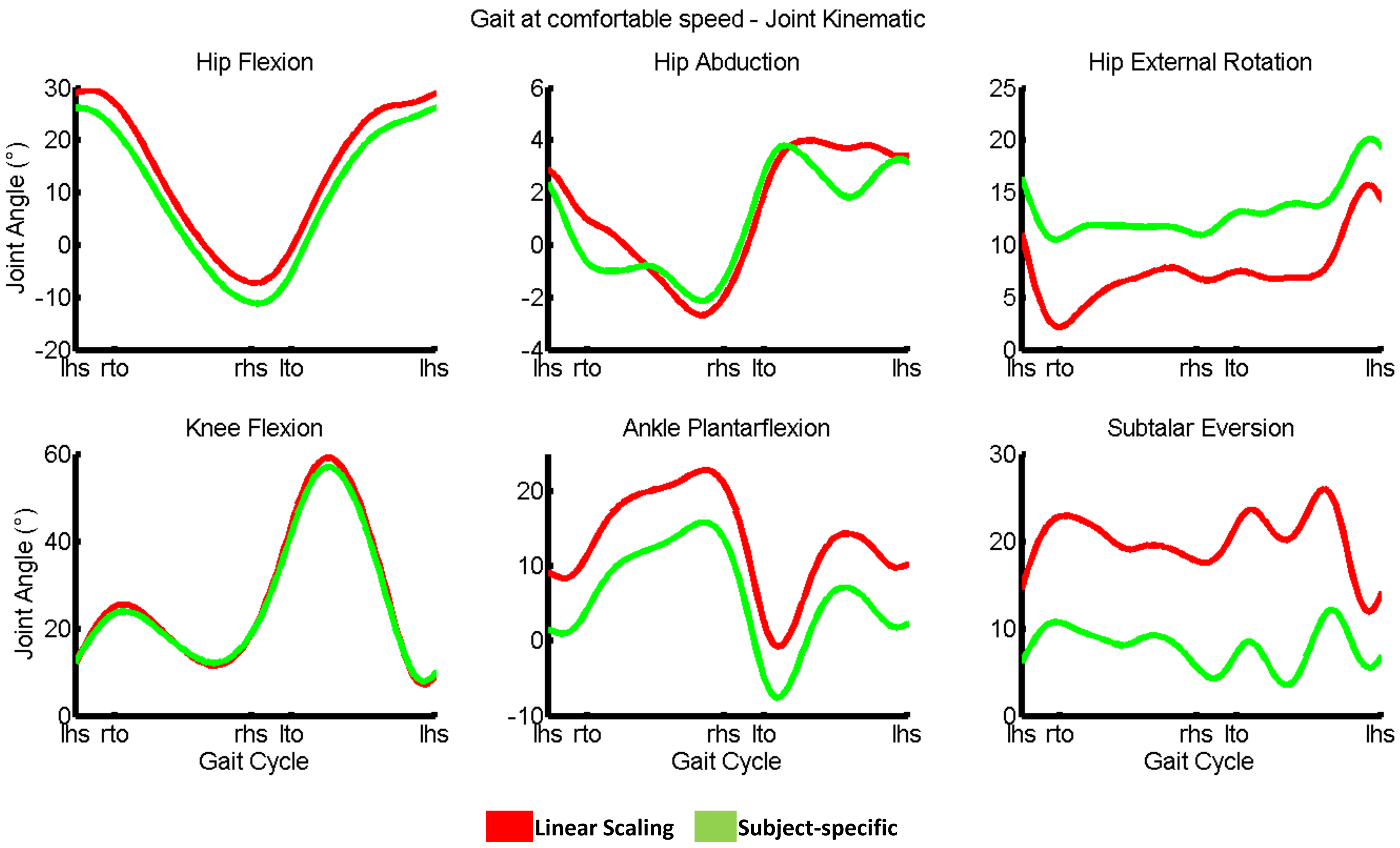
| Muscle Volume | |
|---|---|
| Muscle-tendon parts | max |
| **Quadratus Femoris** | 103.59% |
| **Gluteus Medius** | 71.06% |
| **Tibialis posterior** | 65.11% |
| **Gluteus Minimus** | 65.10% |
| **Vastus Intermedius** | 56.48% |
| **Popliteus** | 56.30% |
| **Obturator Internus** | 45.42% |
| **Extensor Digitorum Longus** | 44.66% |
| **Piriformis** | 43.65% |
| **Flexor Digitorum Longus** | 41.46% |

| Tendon Slack Length | |
|---|---|
| Muscle-tendon parts | max |
| **Quadratus Femoris** | 52.22% |
| **Adductor Brevis Proximal** | 48.17% |
| **Gemellus Inferior** | 40.55% |
| **Adductor Magnus Mid** | 33.28% |
| **Adductor Magnus Proximal** | 32.58% |
| **Obturator Externus Inferior** | 27.30% |
| **Adductor Brevis Mid** | 25.14% |
| **Obturator Internus** | 24.46% |
| **Pectineus** | 24.32% |
| **Obturator Externus Superior** | 24.18% |

| Nominal Muscle Fiber Length | |
|---|---|
| Muscle-tendon parts | max |
| **Quadratus Femoris** | 38.80% |
| **Gemellus Inferior** | 26.68% |
| **Gemellus Superior** | 26.68% |
| **Obturator Externus Inferior** | 26.54% |
| **Obturator Externus Superior** | 23.68% |
| **Adductor Magnus Proximal** | 22.35% |
| **Obturator Internus** | 20.45% |
| **Psoas Major** | 20.38% |
| **Adductor Brevis Proximal** | 18.91% |
| **Piriformis** | 14.92% |

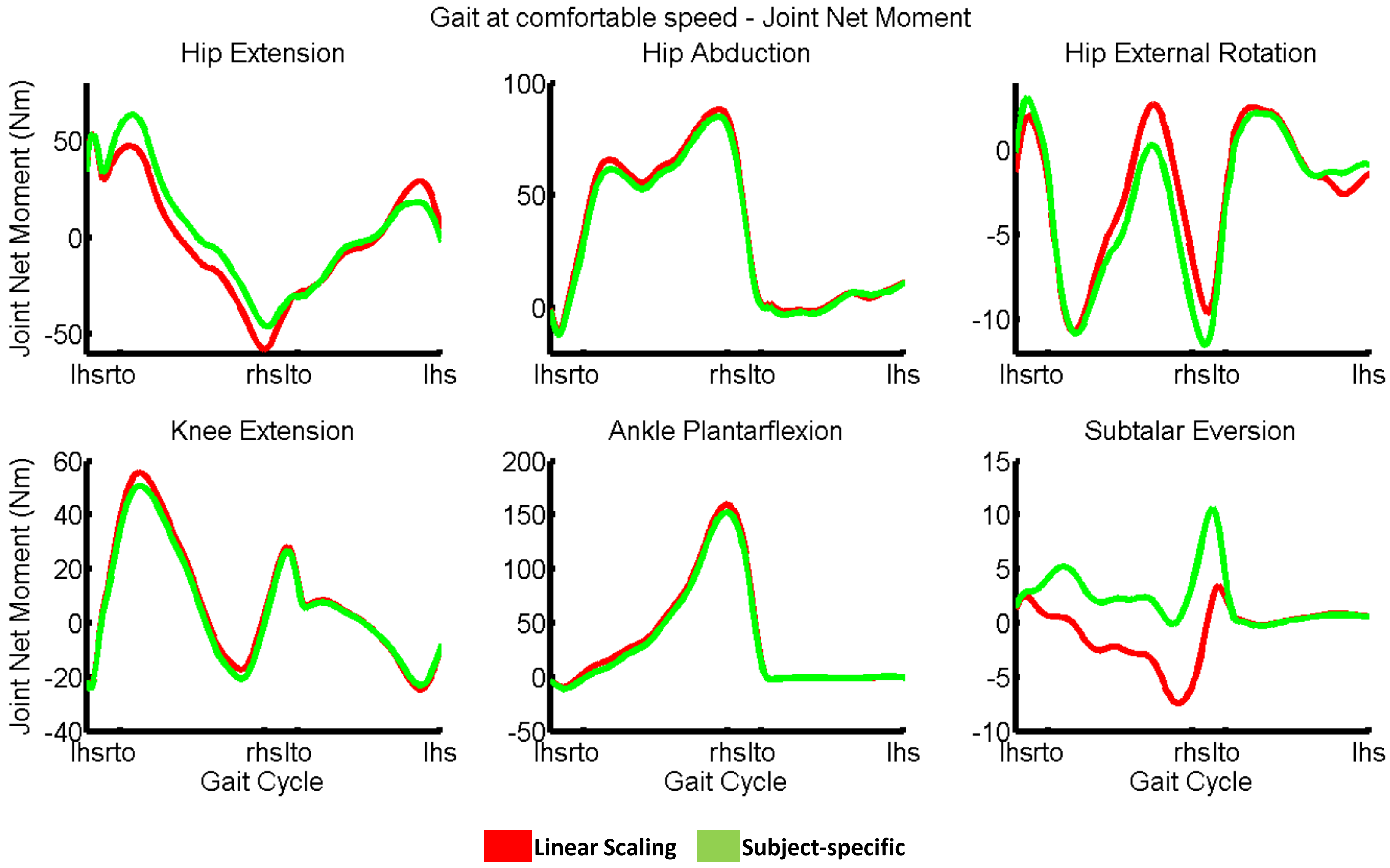
# Healthy subjects-specific models

- Differences between predicted joint kinematics based on optical markers:



# Healthy subjects-specific models

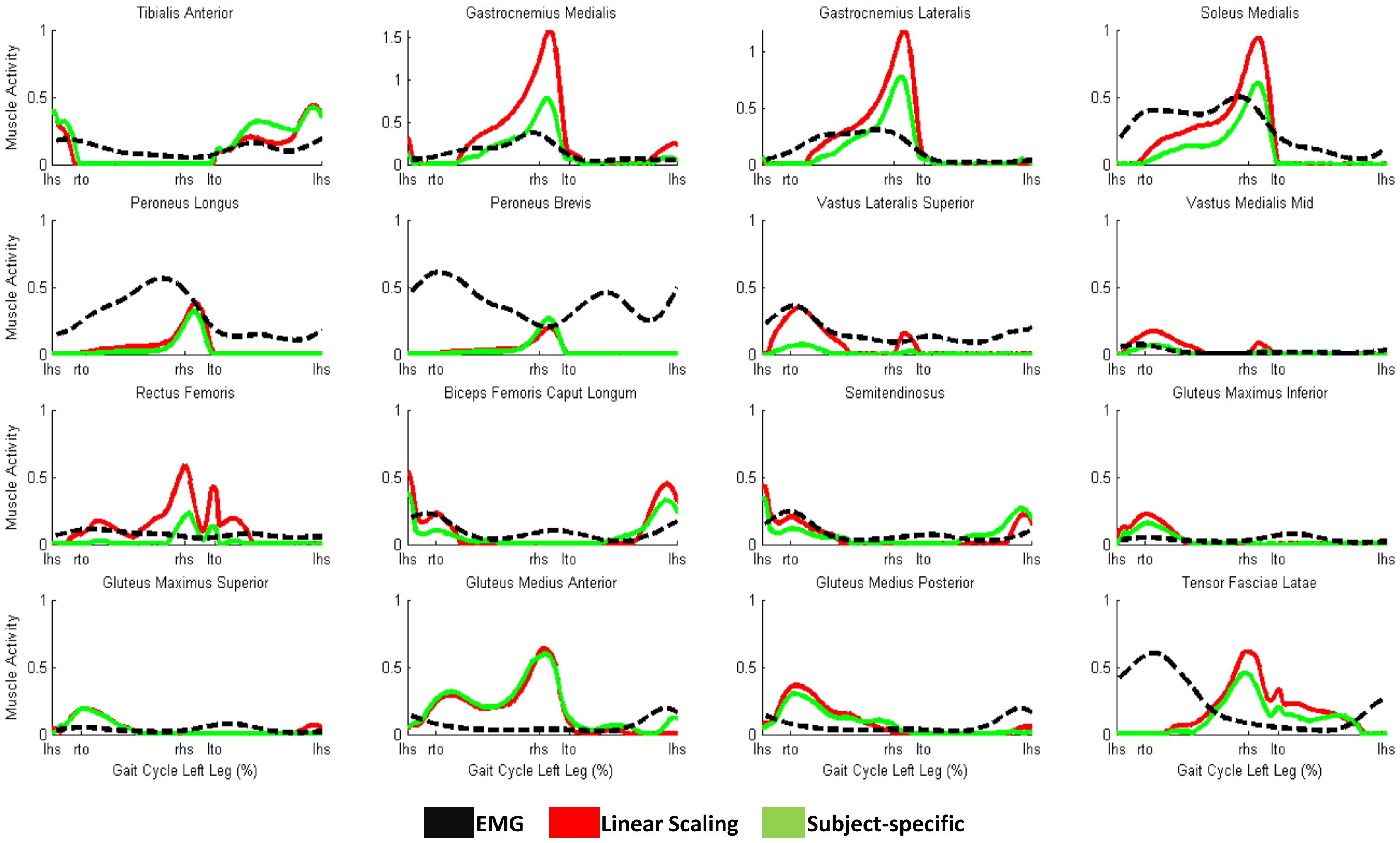
- Differences between predicted joint net moment:

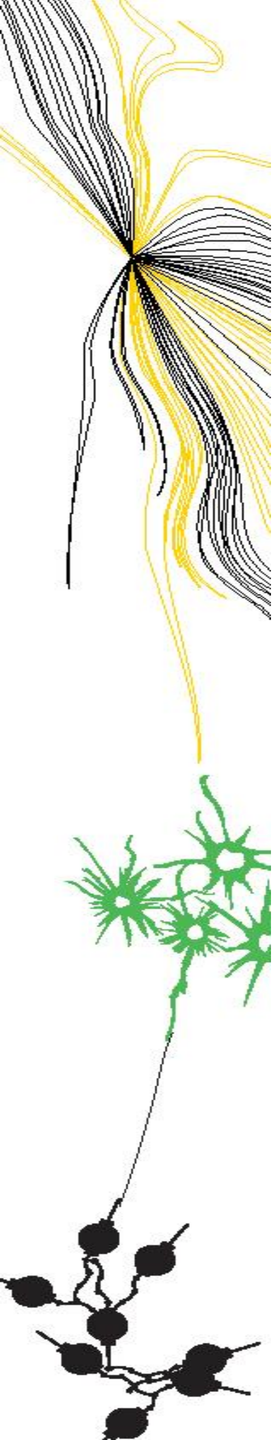


# Healthy subjects-specific models

- Differences between predicted muscle activity:

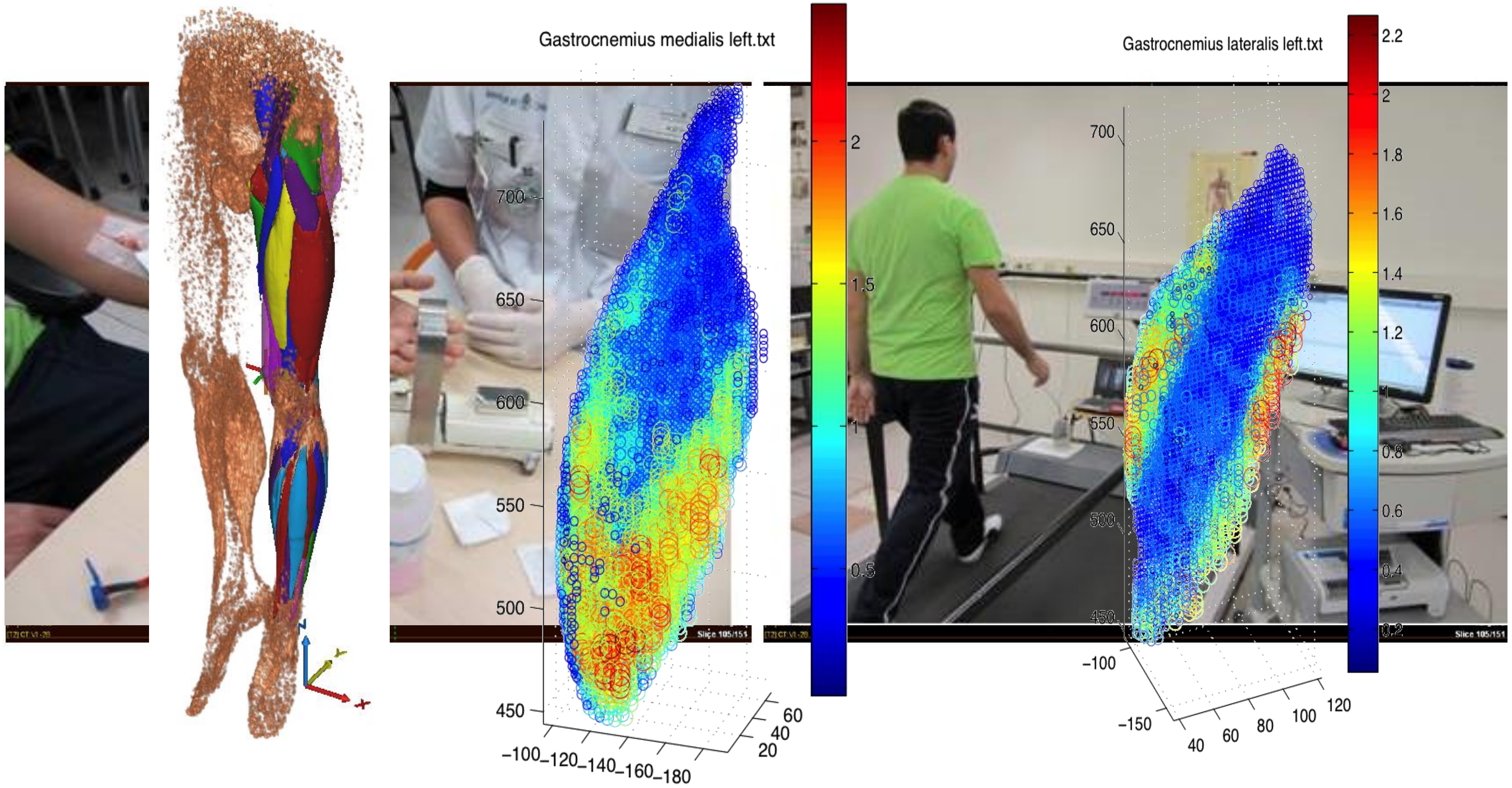
Gait at comfortable speed – Muscle activity



# Validation of subject-specific models using PET scans

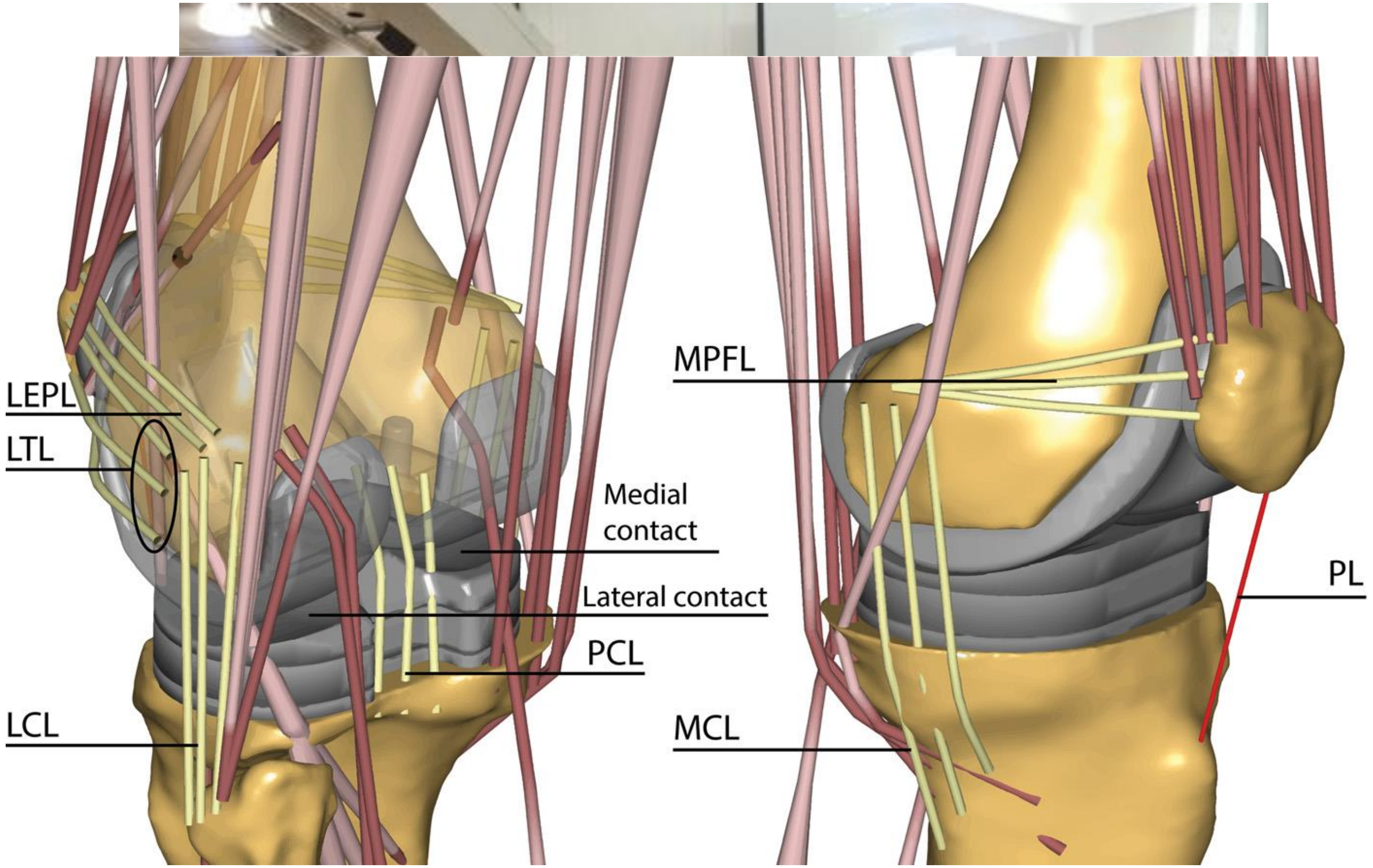
- [18F]-fluorodeoxyglucose radioactive marker accumulates in muscles.
- Positron Emission Tomography detects tracer's concentration.
- Extremely valuable data to validate muscle force prediction.*




*Kolk S., 2015, Medicine and Science in Sports and Exercise, 47(9), 1896-1905

# TLEM*safe* workflow adaptable to include more details

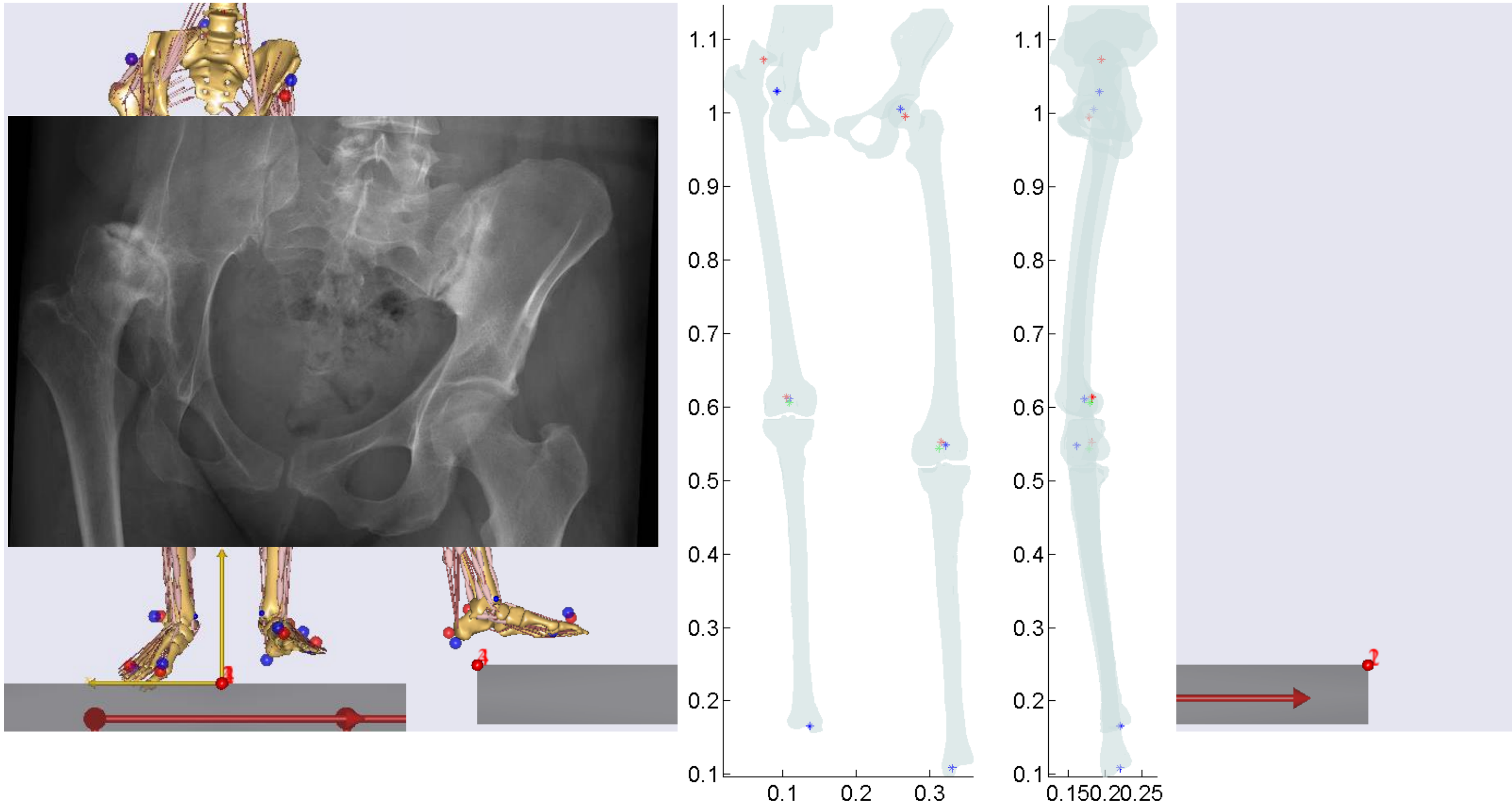
- Combining TLEM 2.0 with 11 DOFs knee complex joint and FDK in AMS*.
- 1st prize at 5th Grand Challenge Competition to Predict In Vivo Knee Loads.




*Marra M.A., et al., ASME. J Biomech Eng. 2015;137(2):020904-020904-12.

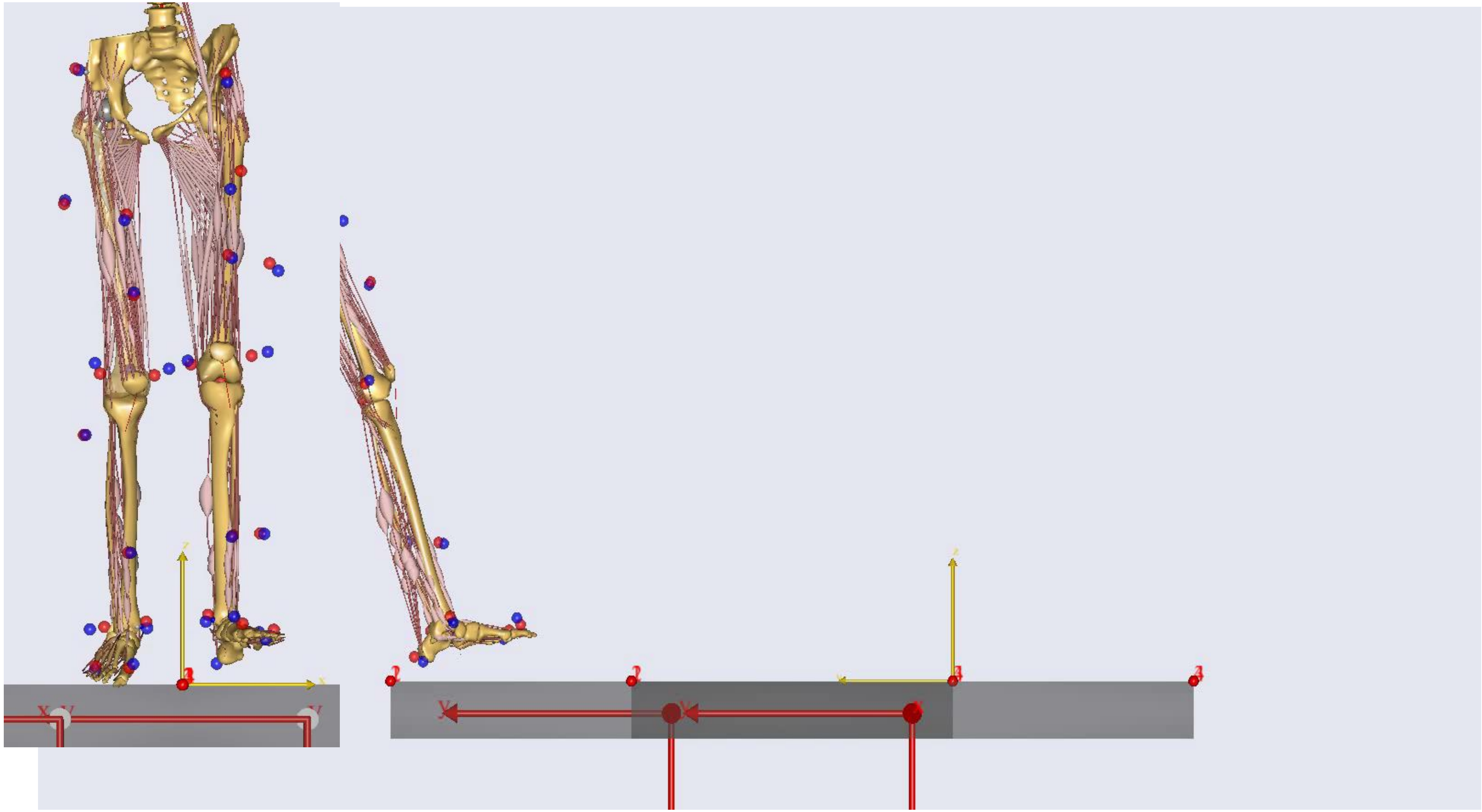
# TLEM*safe* workflow applied to hip dysplasia patients

- Pre-op models based on MRI:



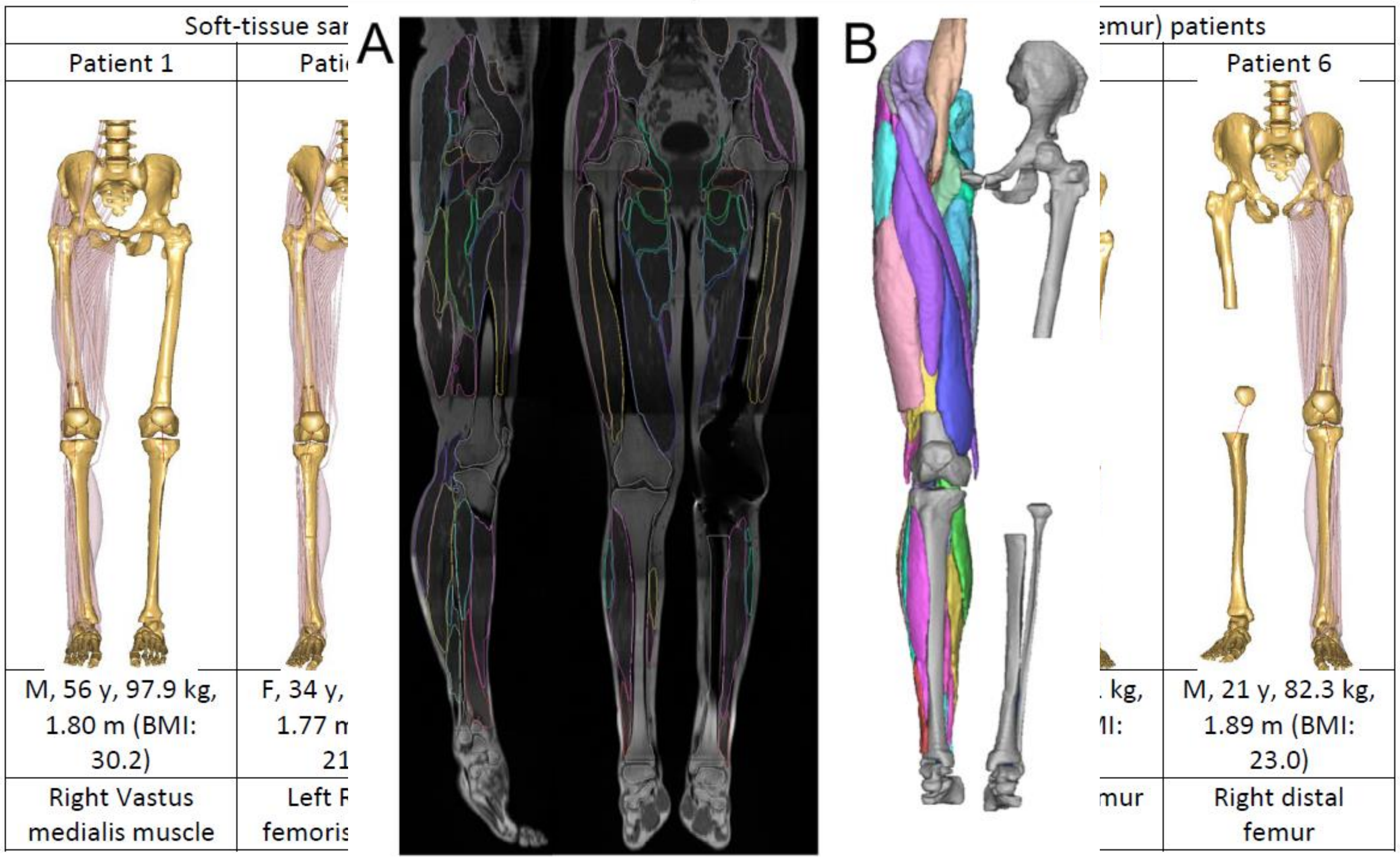
# TLEM*safe* workflow applied to hip dysplasia patients

- Post-op models based on MRI and surgery logs:



# TLEM*safe* workflow applied to sarcoma patients

- Post-op models based on MRI and surgery logs:



# Prediction of functional outcome of surgery*

- Patient-specific musculoskeletal models could assist surgeons in predicting the effect of surgery.

- Problem: how the patients is going to walk (or move) after surgery?

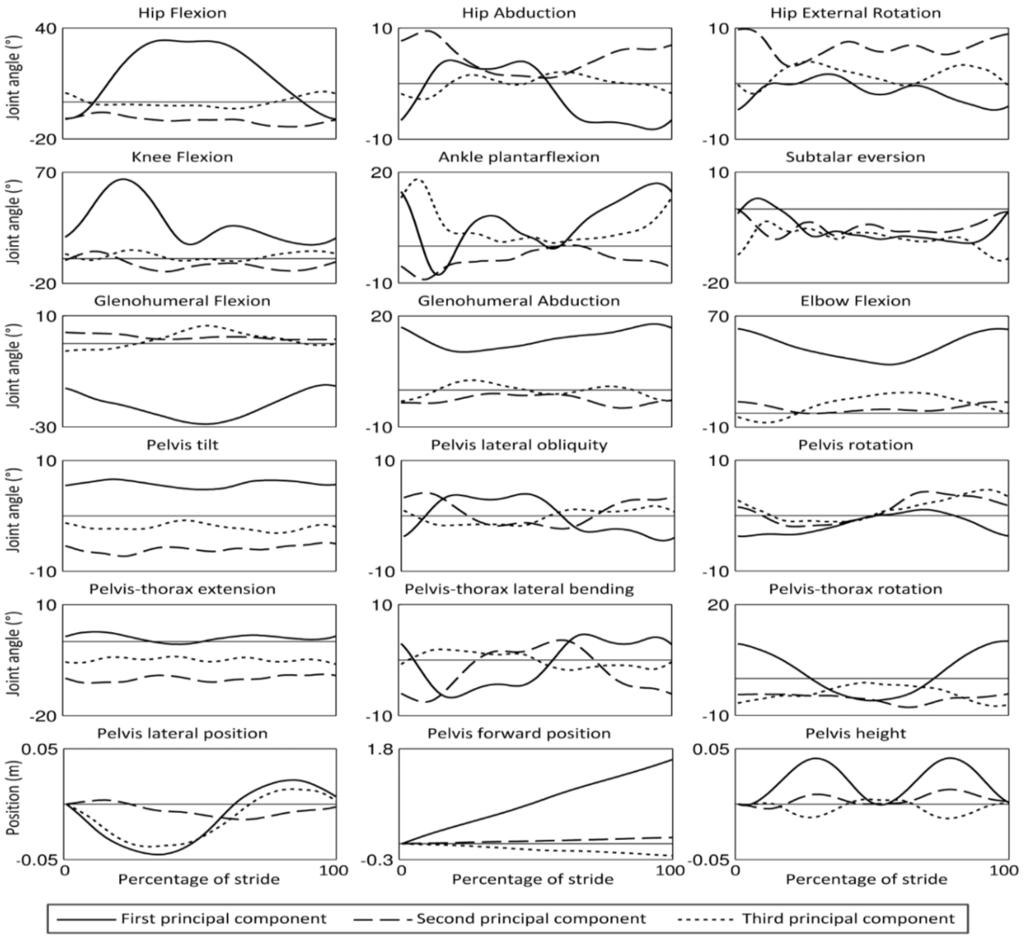
- No data available of the post-op situation.

- Goal: predicting patient-specific walking movement:
    - Prediction of kinematics (joint angles) using PCA;
    - Prediction of kinetics (ground reaction forces and moments).

*Fluit R., "Functional outcome prediction after surgery: a bridge too far?", 2015, PhD Thesis

# Prediction of kinematics using PCA*

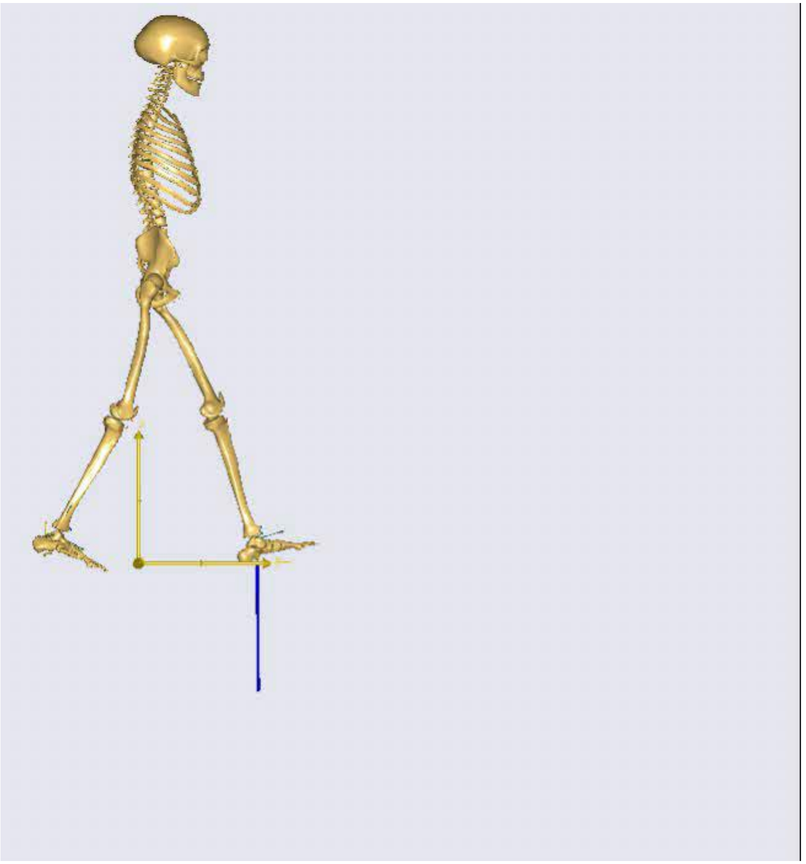
- Principal Component Analysis transforms kinematics measurements dataset into uncorrelated principal components.




*Fluit R., “Functional outcome prediction after surgery: a bridge too far?”, 2015, PhD Thesis

# Prediction of kinematics using PCA*

- Gait reconstruction: linear combination of principal components.



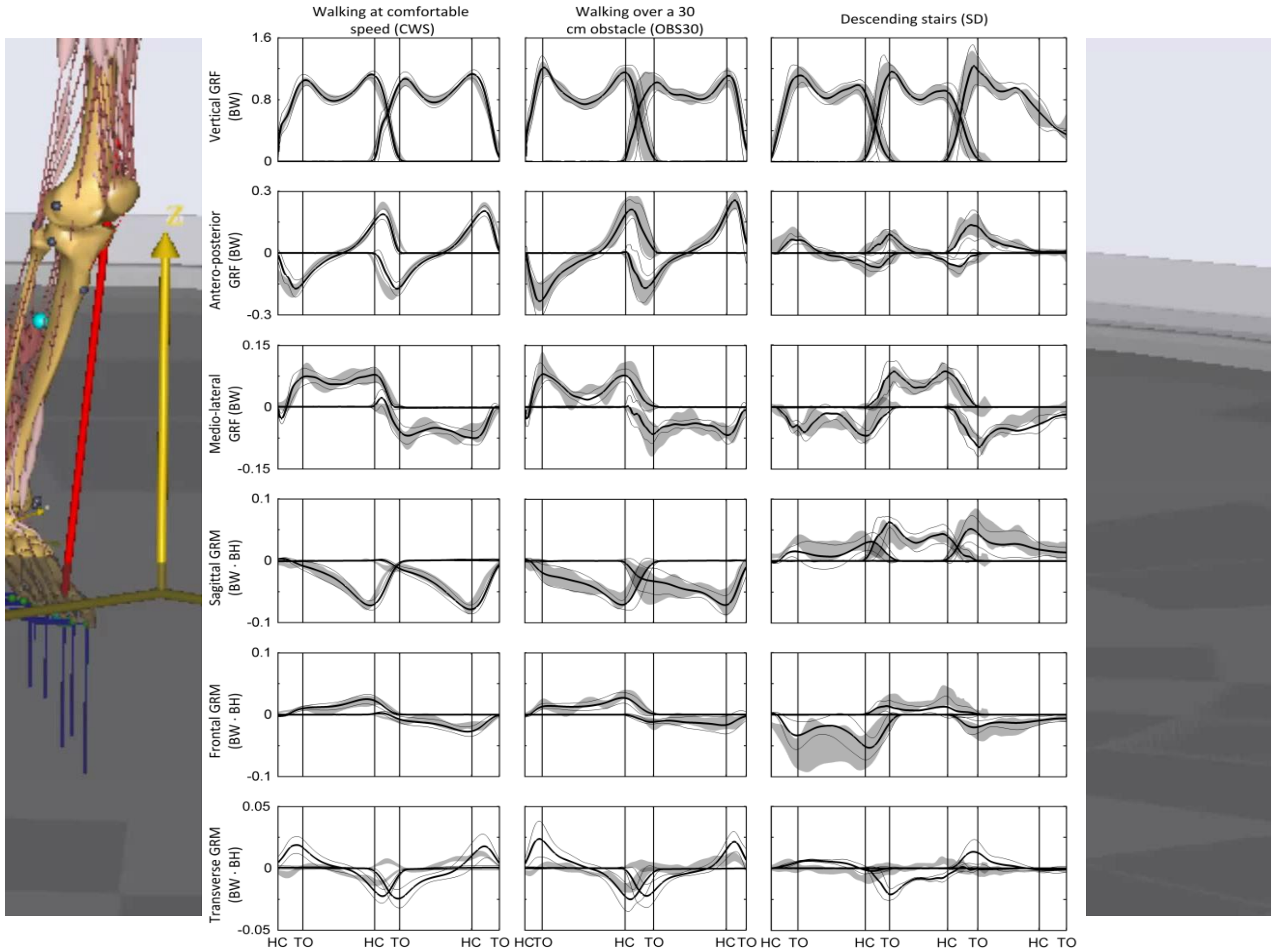
Average gait (1st component)

1st component +
2nd component
4th component

*Fluit R., “Functional outcome prediction after surgery: a bridge too far?”, 2015, PhD Thesis

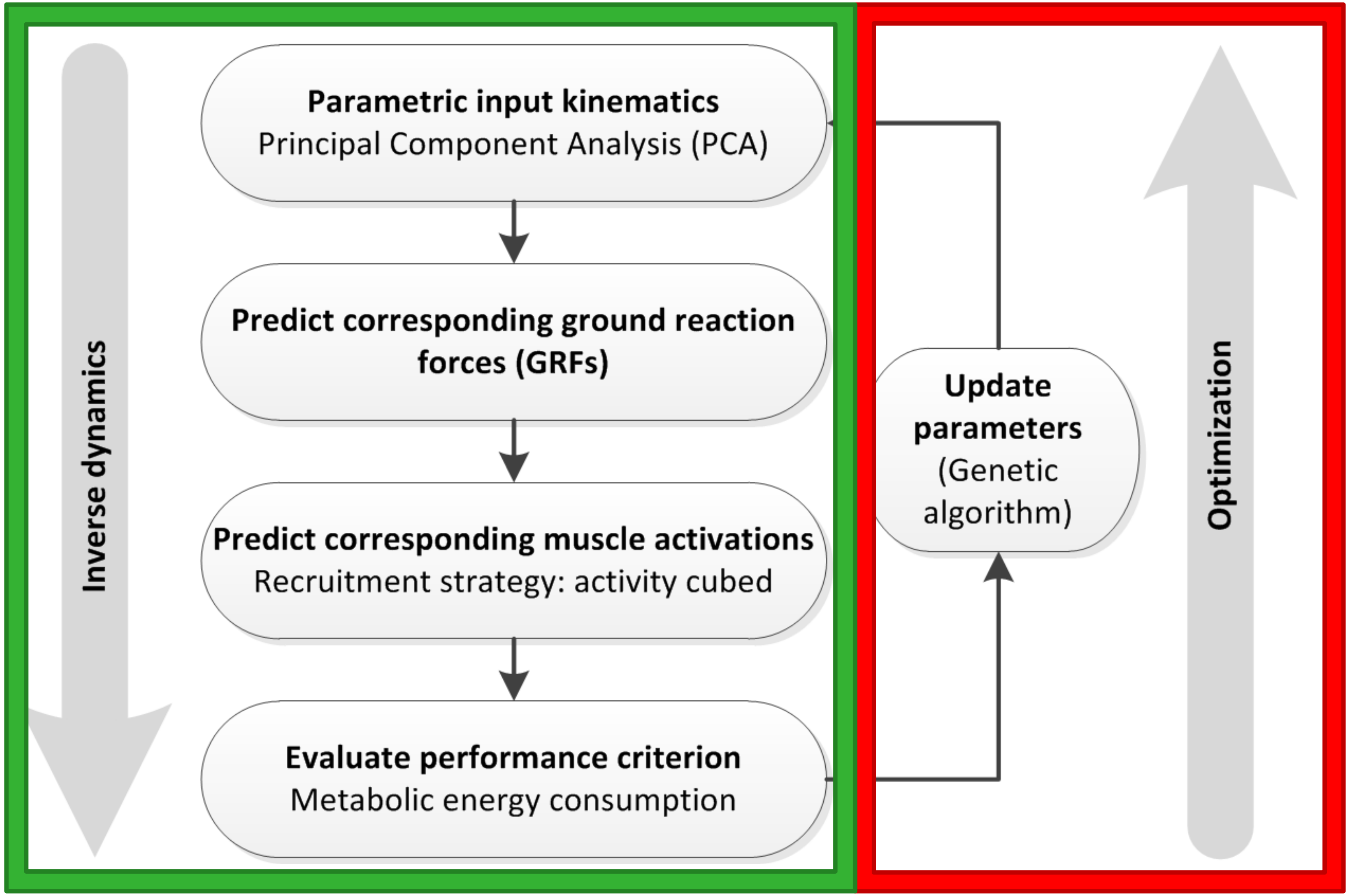
# Prediction of kinetics

- GRFs and GRMs predicted using Newton-Euler equations of motion.*




*Fluit R., et al., 2014, Journal of Biomechanics, Volume 47, Issue 10, Pages 2321-2329.

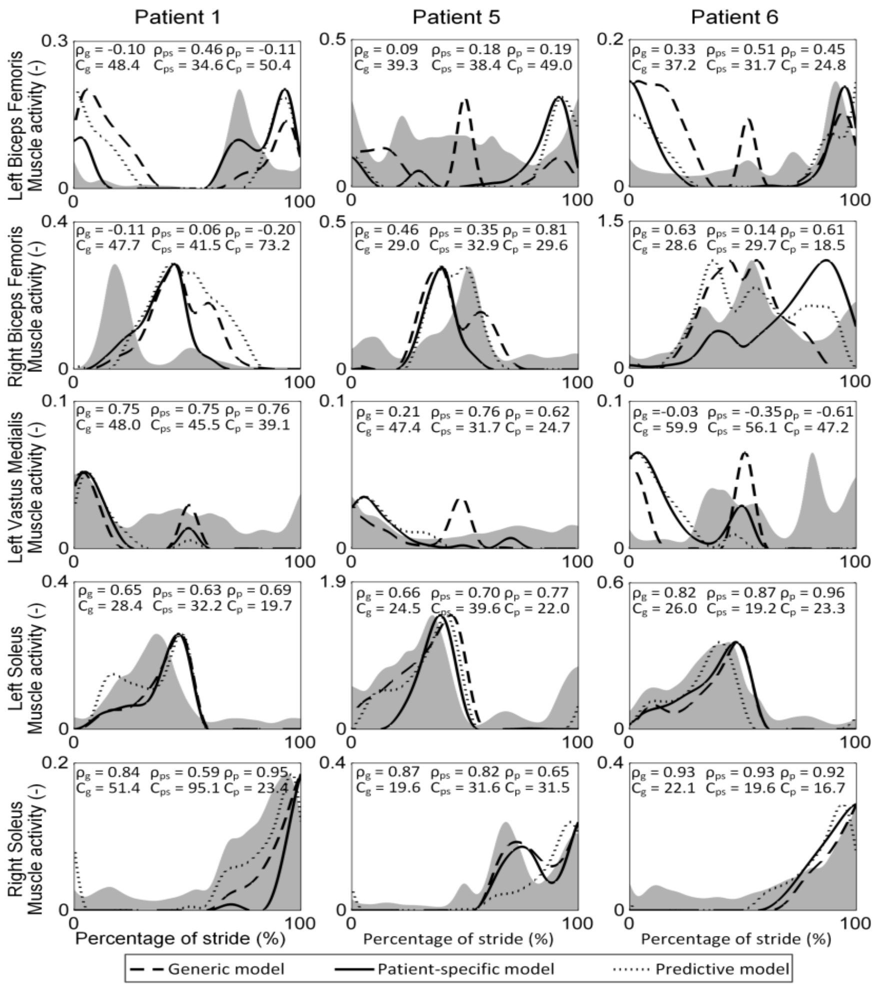
# Optimal inverse dynamics*




*Fluit R., "Functional outcome prediction after surgery: a bridge too far?", 2015, PhD Thesis

# Optimal inverse dynamics*

- Promising tool to predict gait, could be applied to different movements.




*Fluit R., “Functional outcome prediction after surgery: a bridge too far?”, 2015, PhD Thesis

# Conclusion

- TLEM*safe* project achieved many goals in personalized medicine, connecting MS models, virtual reality planning and surgical navigation.

- TLEM 2.0 purposely built to be combined with image-based techniques.
- Fast and semi-automated subject-specific modeling workflow.
- Personalized models showed large improvements compared to linearly scaled model.

- Prediction of kinematics and kinetics for patient-specific models represent a promising tool to assist surgeons in predicting the effect of surgery.

- TLEM 2.0 available for non-commercial usage at www.tlemsafe.eu.
- TLEM*safe* functional datasets available for research collaboration.
- TLEM*safe* coordinator: nico.verdonschot@radboudumc.nl

# Special thanks to TLEM*safe* partners


Radboudumc
university medical center

WARSAW UNIVERSITY OF TECHNOLOGY

ANYBODY™ TECHNOLOGY

Materialise Software

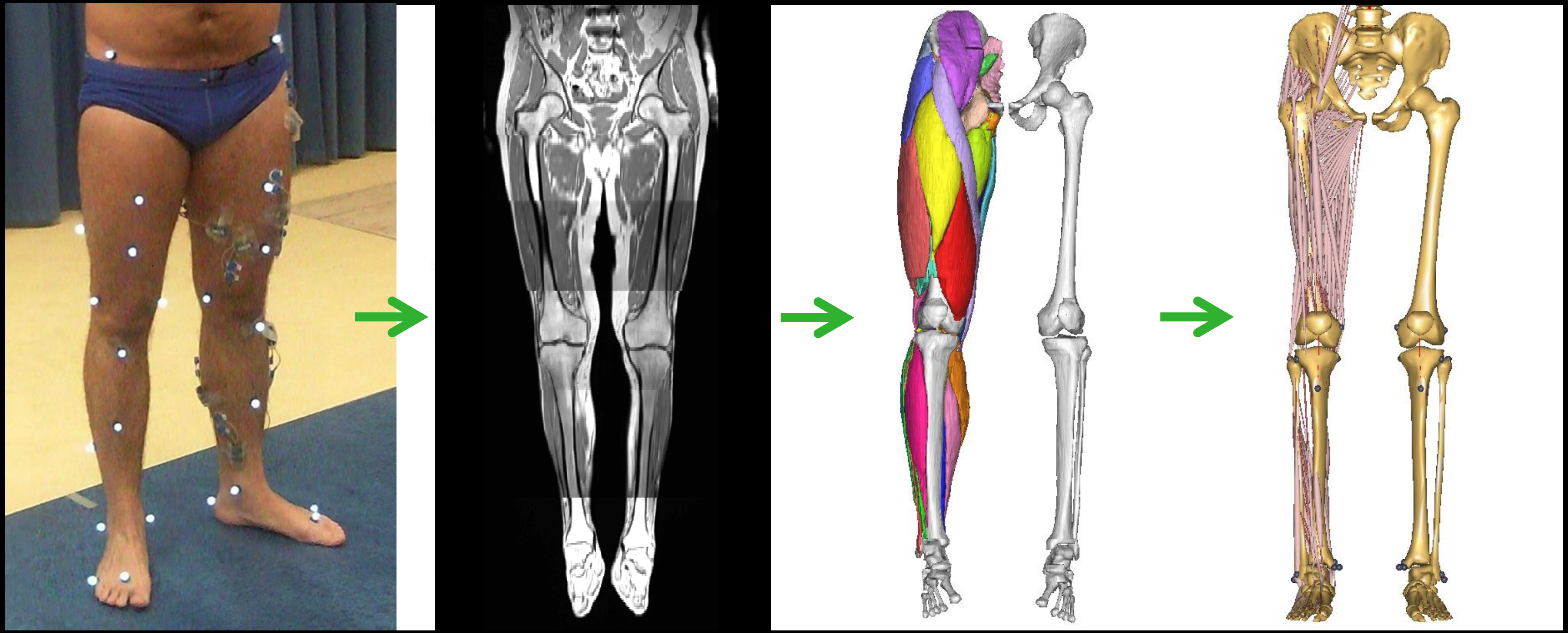
BRAINLAB

UNIVERSITY OF TWENTE.

Biomechanical Engineering

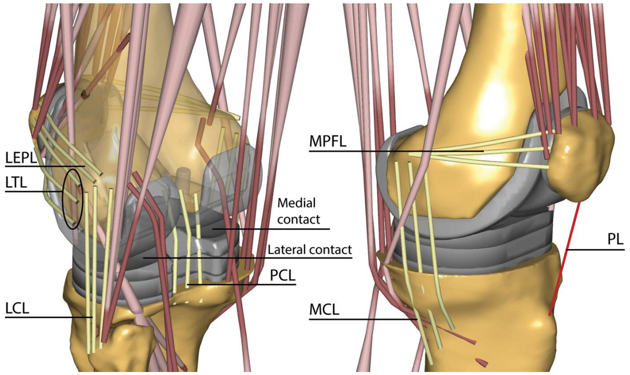
# TLEM*safe* legacy

Towards personalization of musculoskeletal models and prediction of functional outcome



# Impact of the TLEM2.0 model

Instrumental for winning the 5th Knee Grand Challenge at the World Congress of Biomechanics in Boston 2014.




Previous webinars:

**Evaluation of predicted knee kinematics and ligament length changes by force-dependent kinematics in vitro** (Valentine Vanheule, K.U. Leuven, 13. November, 2014)

**Patient-specific Musculoskeletal Modelling of Total Knee Arthroplasty using Force-dependent Kinematics** (Michael Skipper Andersen, Aalborg University, 09. September, 2014)

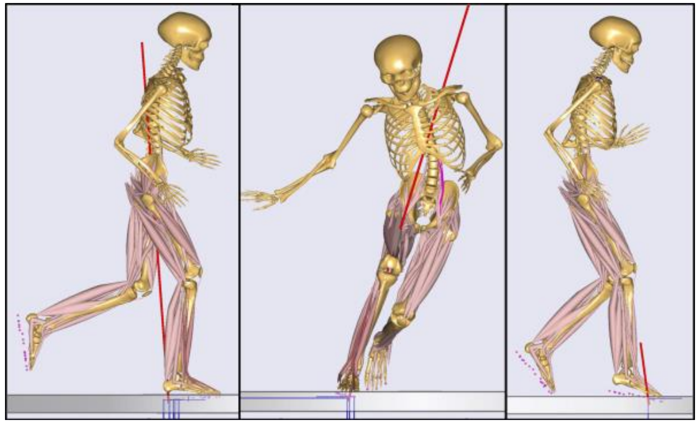
*Available on www.anybodytech.com*

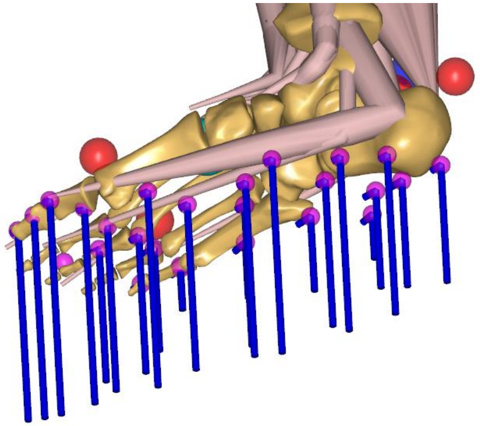
# Ground reaction force prediction

Upcoming webcast:

**Ground reaction force prediction with the AnyBody Modeling System.**
*(Assoc. Prof. Michael Skipper Andersen and Sebastian Skals, M.Sc.)*

*October 6th. Registration is open ([www.anybodytech.com](http://www.anybodytech.com))*





Ground reaction force prediction by Dr. Rene Fluit

Journal of Biomechanics 47 (2014) 2321–2329

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www.JBiomech.com

Prediction of ground reaction forces and moments during various activities of daily living

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article info

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Musculoskeletal model
Inverse dynamics
Dynamic consistency
Activities of daily living

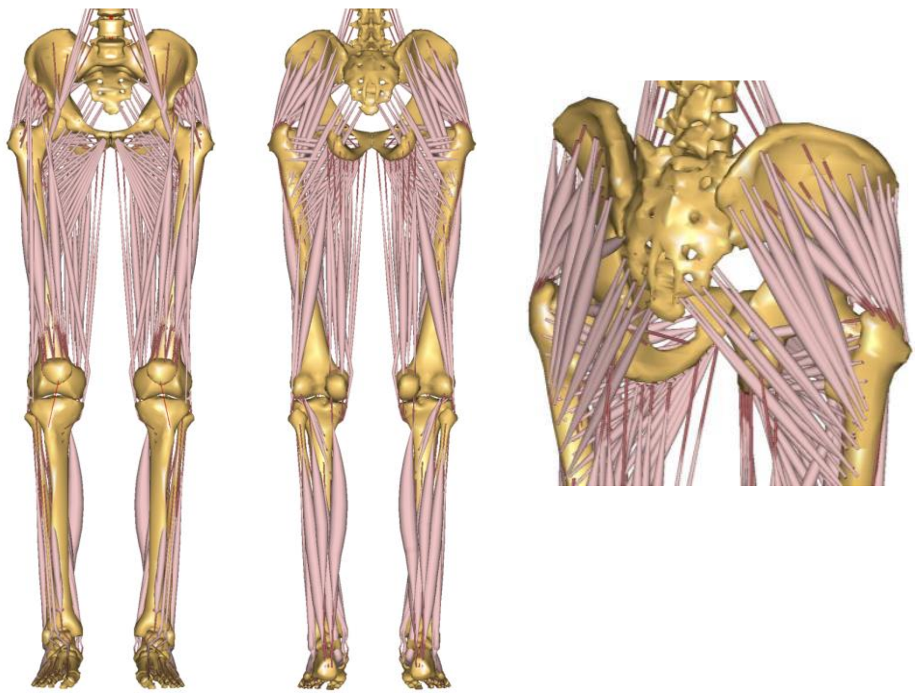
abstract

Inverse dynamics based simulations on musculoskeletal models is a commonly used method for the analysis of human movement. Due to inaccuracies in the kinematic and force plate data, and a mismatch between the model and the subject, the equations of motion are violated when solving the inverse dynamics problem. As a result, dynamic inconsistency will exist and lead to residual forces and moments. In this study, we present and evaluate a computational method to perform inverse dynamics-based simulations without force plates, which both improves the dynamic consistency as well as removes the model's dependency on measured external forces. Using the equations of motion and a scaled musculoskeletal model, the ground reaction forces and moments (GRF&Ms) are derived from three-dimensional full-body motion. The method entails a dynamic contact model and optimization techniques to solve the indeterminacy problem during a double contact phase and, in contrast to previously proposed techniques, does not require training or empirical data. The method was applied to nine healthy subjects performing several Activities of Daily Living (ADLs) and evaluated with simultaneously measured force plate data. Except for the transverse ground reaction moment, no significant differences (P4 0.05) were found between the mean predicted and measured GRF&Ms for almost all ADLs. The mean residual forces and

# Making TLEM2.0 model available

AnyBody implementation will be released in AMMR:

- AMMR beta release expected during autumn.
- Fully integrated with the other body parts
- Both versions of the TLEM model are still available
- Supports the TLEMsafe workflow for subject specific modeling



For research/academic access to the dataset?

Contact **Prof. Dr. Ir. Nico Verdonschot** for collaboration:

nico.verdonschot@radboudumc.nl

www.tlemsafe.eu

# Time for questions: