ENGINEERING THE INTERACTION BETWEEN FOOTWEAR DESIGN, SOIL & TURF PROPERTIES AND HUMAN'S BIOMECHANICS

Prof. Dr.-Ing. Veit SENNER

TECHNICAL UNIVERSITY OF MUNICH
TUM School of Engineering and Design
Professorship Sport Equipment and Materials

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BIOMED 2023

SCI SYNOPSIS

International Conference on
Biomedical Science and Engineering

The storyline of my today‘s talk…

I. The relationships between footwear design and
… the mechanical properties of various sport surfaces,
… the risk to suffer injuries,
… the likelihood to undergo long termed damages
is not yet understood. We and others are working on it.

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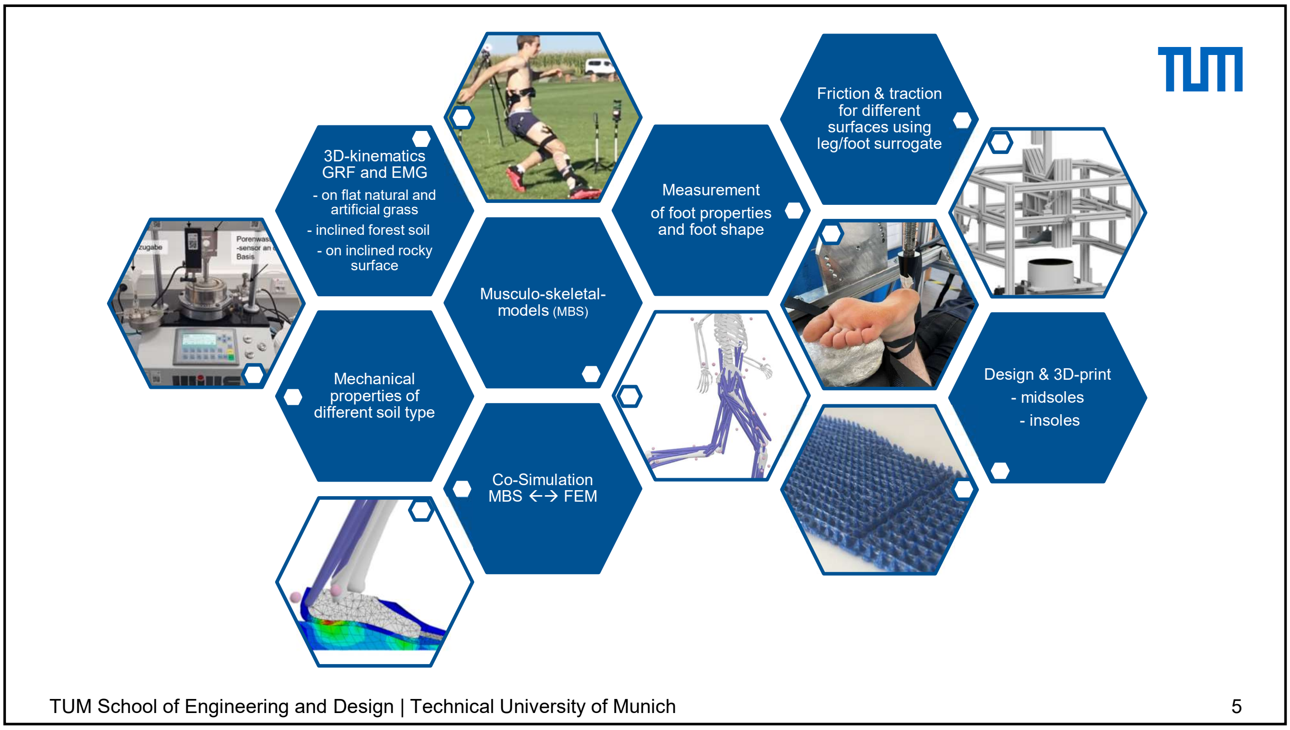
II. Footwear may be adjusted to the individuum and being optimized to the boundary conditions of the physical activity / type of sports.

III. Improved research methods, innovative materials and new production technologies - such as 3D-printing – offer the opportunity to achieve this goal.


3D-kinematics
GRF and EMG
- on flat natural and artificial grass
- inclined forest soil
- on inclined rocky surface
Musculo-skeletal-models (MBS)
Measurement of foot properties and foot shape
Friction & traction for different surfaces using leg/foot surrogate
Mechanical properties of different soil type
Co-Simulation MBS ←→ FEM
Design & 3D-print
- midsoles
- insoles
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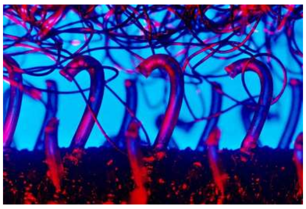
PART I
Friction, traction and damping measurements to categorize sport shoes and to investigate new type of artificial turf

Sorry: Some physics is needed (1) …

friction = adhesion + cohesion

Vacuum cup



Velcro

Source: Natural Philo - Eigenes Werk, CC BY-SA 3.0
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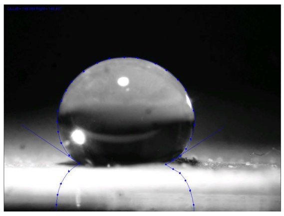

Drop on lotus flower

Source: By Na2jojon - Own work, Public Domain,
https://commons.wikimedia.org/w/index.php?curid=12363268

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Sorry: Some physics is needed (2) …

traction = friction + form fit

Source: https://www.fitforfun.de/files/images/

Source:
https://pixabay.com/de/schuhabdruck-sohle-abdruck-spur-3482282/

Source:
https://images.app.goo.gl/TKGNHVmfowWoJHcb9

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https://images.app.goo.gl/1XpPADsqWDnFaPDX7

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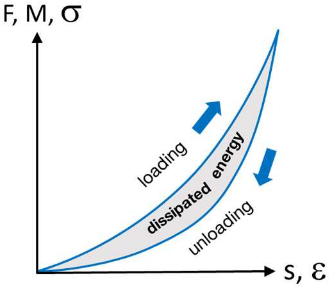
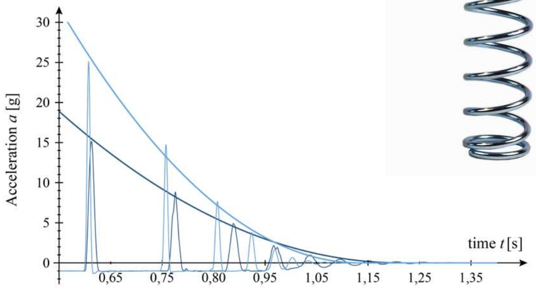
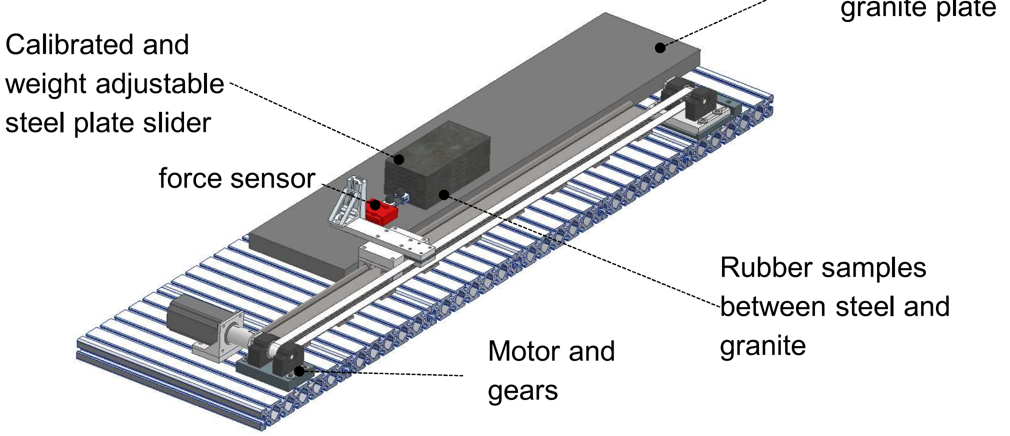
Sorry: Some physics is needed (3) …

Damping / Hysteresis ≠ **Elasticity**

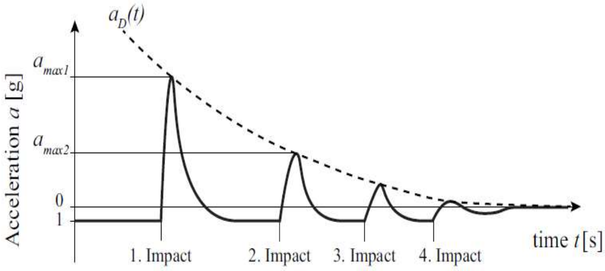




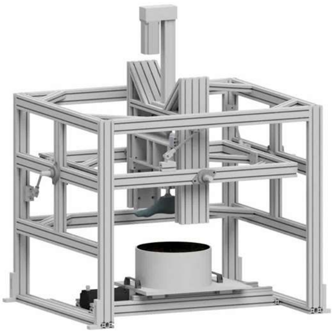
Dynamic friction test (DIN 51131:2014-02)



Pneumatic impacter tests for measuring damping properties

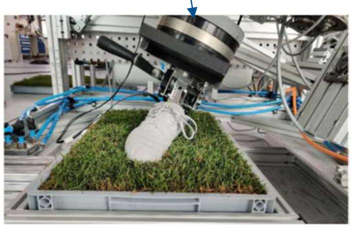


Traction measurements with TUM surrogate (1)



Up to 2500 N vertical load

Six component load cell



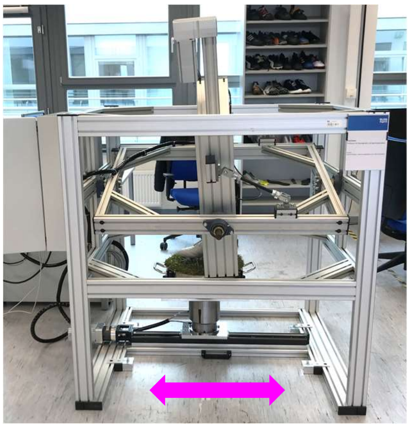
Abducted leg – simulating a side-cut manoeuvre

foot model

spring steel to simulate forefoot

silicone covering

Traction measurements with TUM surrogate (2)

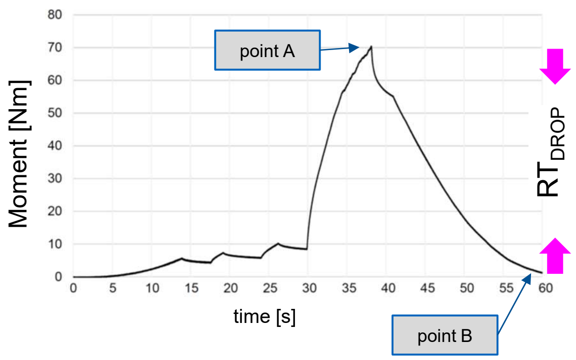


Twisting Moment [Nm]

One example parameter: *Rotational Traction Drop*

- When increasing the applied external twisting moment, the shoe (at point A) loses the grip and the measured value drops.
- If this drop occurs within a very short time or is very pronounced, then loosing balance may happen.

Measured Rotational Traction



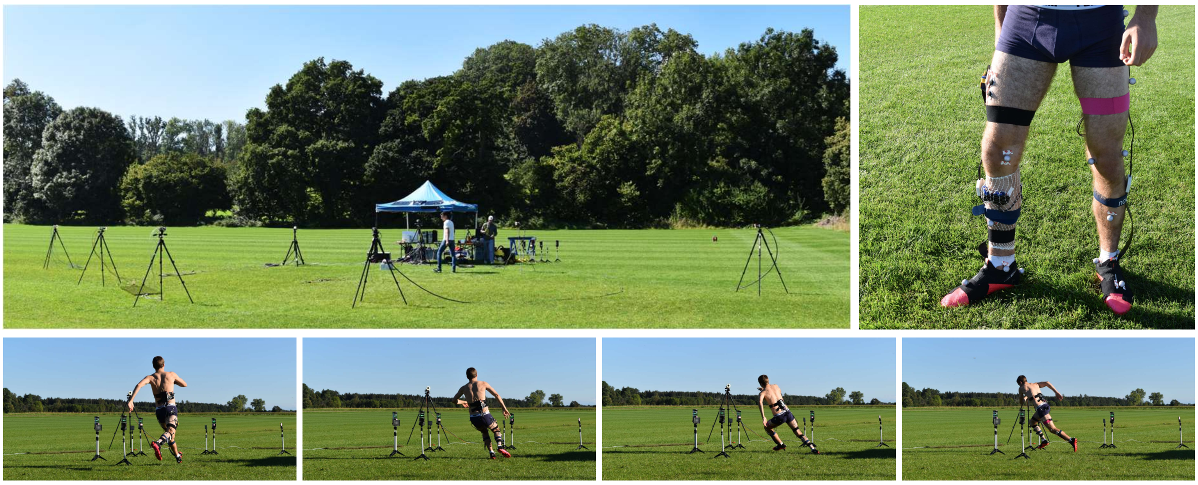
PART II

Development and evaluation of a <u>biopolymer</u> hybrid turf

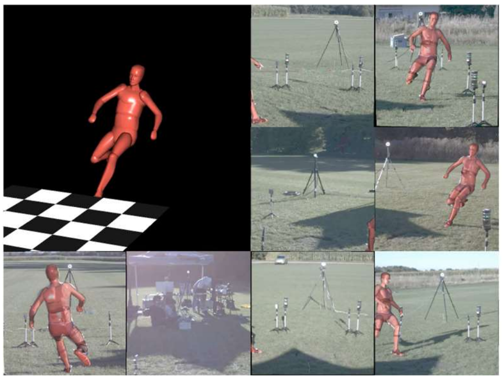
Bahador KESHVARI, M.Sc.
Ph.D student

Valentin WOHLGUT, M.Sc.
Ph.D student

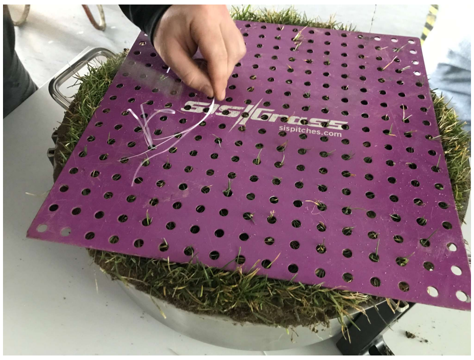
3D-kinematics, GRF and EMG - on flat natural and artificial grass

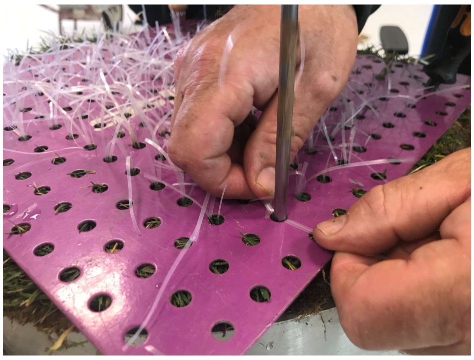


Slow motion of a cutting movement

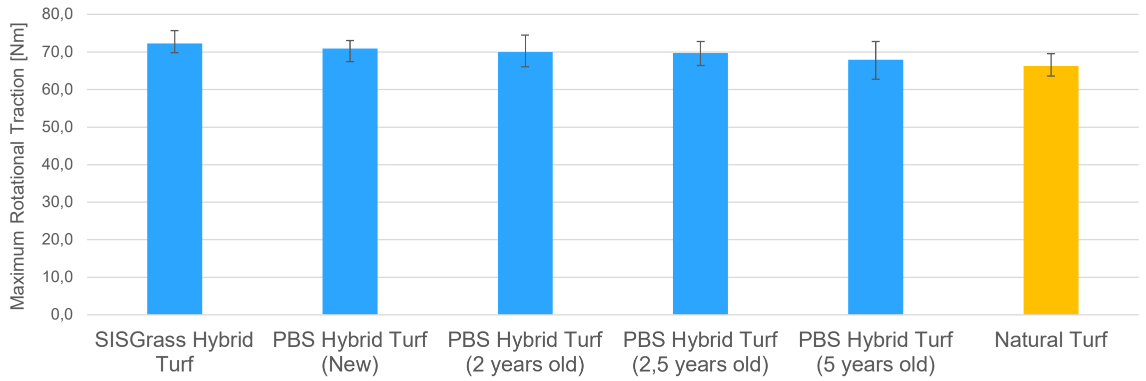


Fibre-stitching with handtool





Traction tests reveal good long term behaviour of *Hybrid Turf*



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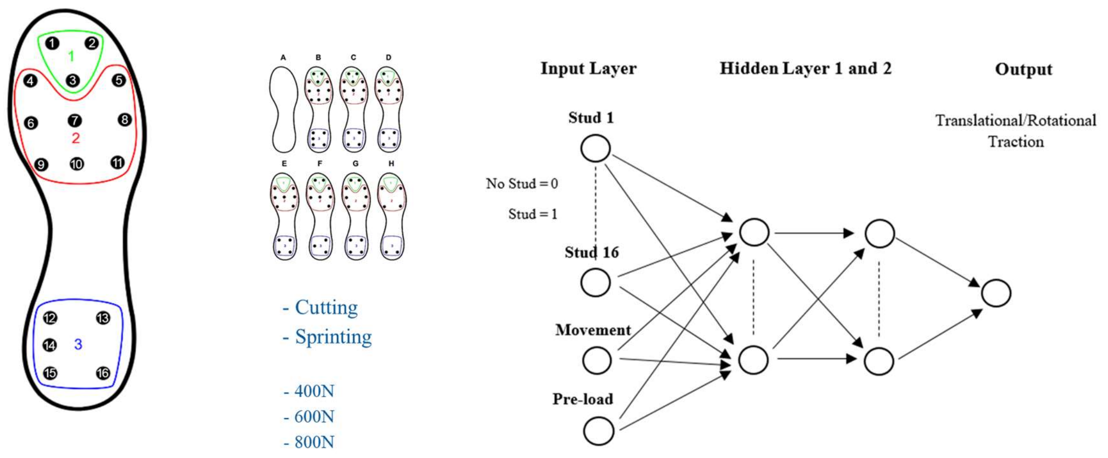
Stud Design Investigations



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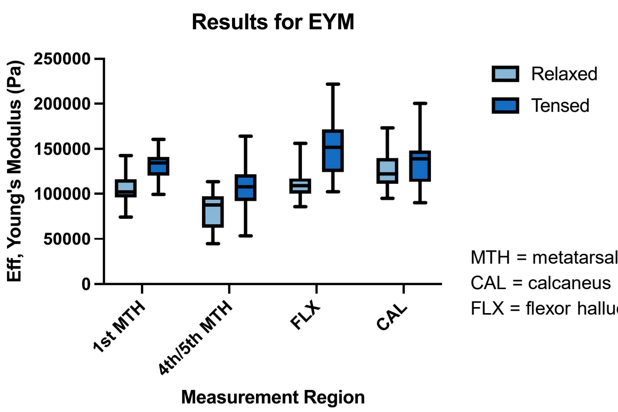
Measurement of foot sole properties

Study is currently „in review“ for
Springer Nature Scientific Reports



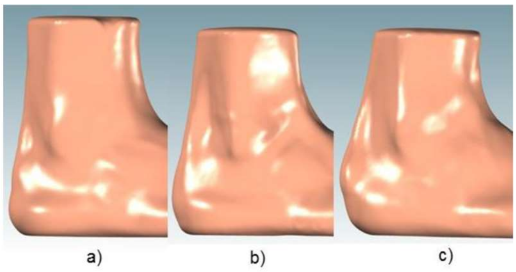
MTH = metatarsal head
CAL = calcaneus
FLX = flexor hallucis longus

Determination of the foot‘s morphology

D. Blob (2016) The influence of individual heel shapes on the placement of the foot in the shoe. Unpublished Master’s Thesis, TUM.

In co-operation with: adidas

- n=301 professional soccer players
- Classified into three different heel shapes:
  a) flat
  b) normal
  c) prominent.



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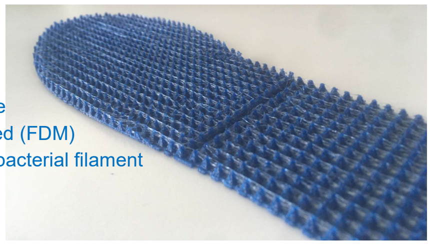
ZIM Zentrales Innovationsprogramm Mittelstand

Proprioceptive 3D-printed insoles



Prototype
3D-printed (FDM)
with antibacterial filament

Goals of „FitFeet“ insole:

- **Increase blood circulation** at the plantar foot
  - Acupressure as a therapeutic approach for foot pain (e.g. plantar fasciitis)
  - Alleviate the sensation of cold feet
- **Support perceptual-motor functions**
  - Enhance sensation when it has diminished due to diabetes or surgery.
- **Improve shoe hygiene** (reduction of athlete‘s foot or foot odor)
  - The FitFeet-insole ought to suppress the growth of bacteria inside the shoe due to its antibacterial properties.

Christian FRITZSCHE, M.Sc
Ph.D student
christian.fritzsche@tum.de

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Project *FitFeet*: Methods overview

Blood circulation

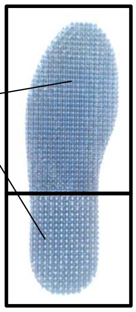
An increase in blood circulation is inferred from the rise in skin temperature, which is determined using an **infrared camera** and compared to the results of **LASER SPECKLE CONTRAST IMAGING (LSCI)**

Perceptual motor functions

Participants undergo a series of **stability tests,** such as the single leg stance on a freely oscillating plate (Posturomed). Performance is assessed based on the ability to restore stability after an external disturbance

Shoe hygiene

Currently, two antibacterial bio additives (pine resin and peppermint oil) are being tested against a state-of-the-art additive (silver) when mixed into a base polymer (PE or PP). The different mixtures will be compared in an **antibacterial test**



Fadillioglu, C., Kanus, L., Möhler, F., Ringhof, S., Hellmann, D., & Stein, T. (2022). Influence of Controlled Stomatognathic Motor Activity on Sway, Control and Stability of the Center of Mass During Dynamic Steady-State Balance-An Uncontrolled Manifold Analysis. *Frontiers in human neuroscience*, *16*, 868828. https://doi.org/10.3389/fnhum.2022.868828

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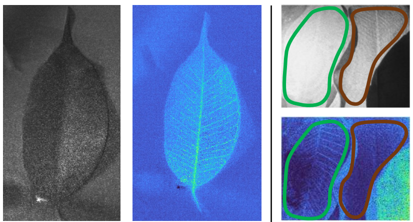
Project: *FitFeet*

Method: Laser Speckle Contrast Imaging (LSCI)

- Tissue is illuminated with laser light
- Scattered light creates speckle pattern allowing to estimate flow-related changes
  - ➢ Areas with **high contrast ↔ slow blood flow**
  - ➢ Areas with **low contrast ↔ fast blood flow**
- Provides **qualitative** assessment of blood flow dynamics, expressed in arbitrary units
- Non-invasive and real time imaging technique

OUTLOOK:

- Measure quantitatively blood speed by **combining LSCI with Particle Image Velocimetry (PIV)**
- Low-Cost-Design



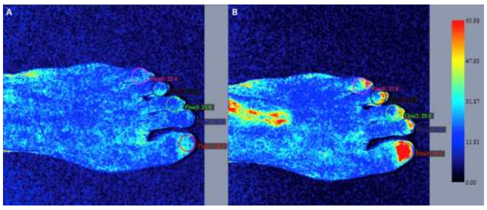
Original Laser Speckle Image with industrial camera (Matrix Vision)

After Speckle Contrast analysis

Original Laser Speckle Image with modified Low-Cost-Camera (Webcam < 9€)

After Speckle Contrast analysis: Able to distinguish between the fresh (green) and dried (brown) leaf

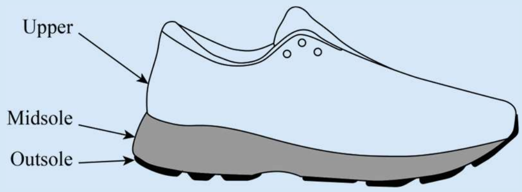
Peripheral nerve blocks cause sympathetic block and vasodilatation, thus increasing local blood flow. Left image before sciatic block, right image 5min after sciatic block



Wu, X., Li, J., Joypaul, K., Bao, W. W., Wang, D., Huang, Y. J., Li, P. C., & Mei, W. (2018). Blood flow index as an indicator of successful sciatic nerve block: a prospective observational study using laser speckle contrast imaging. *British journal of anaesthesia*, *121*(4), 859–866. https://doi.org/10.1016/j.bja.2018.05.065

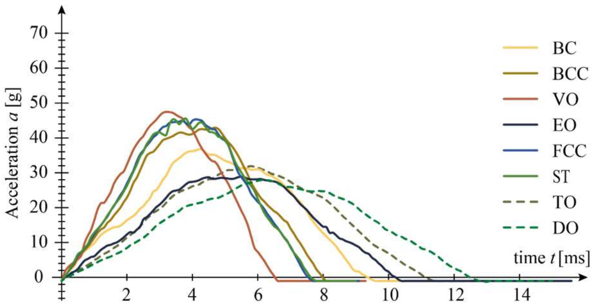
The next logical step…

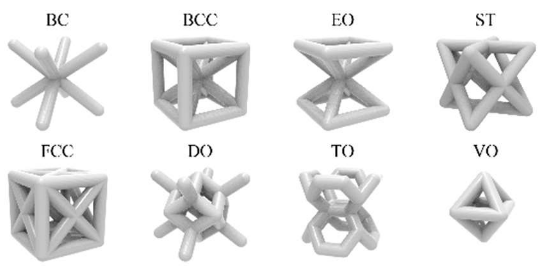
3D-printed running shoe with individualized midsole



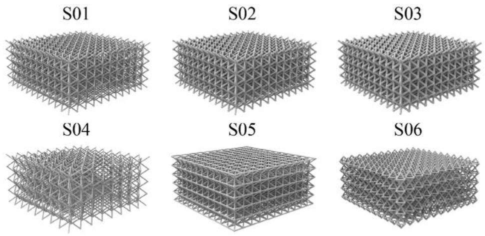
Robin COMPEYRON, M.Sc
Ph.D student

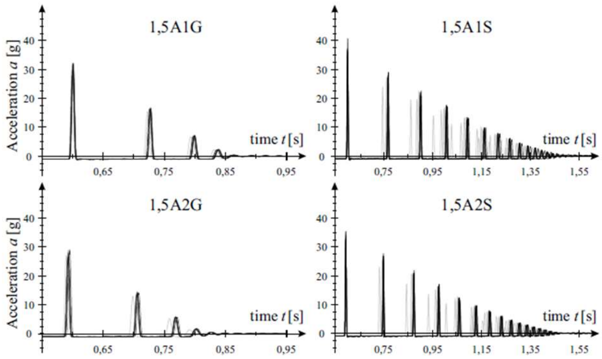
Acceleration-Time Curves for different cell unit geometries



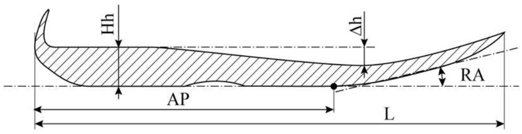


Rendering of six different Lattice Structures



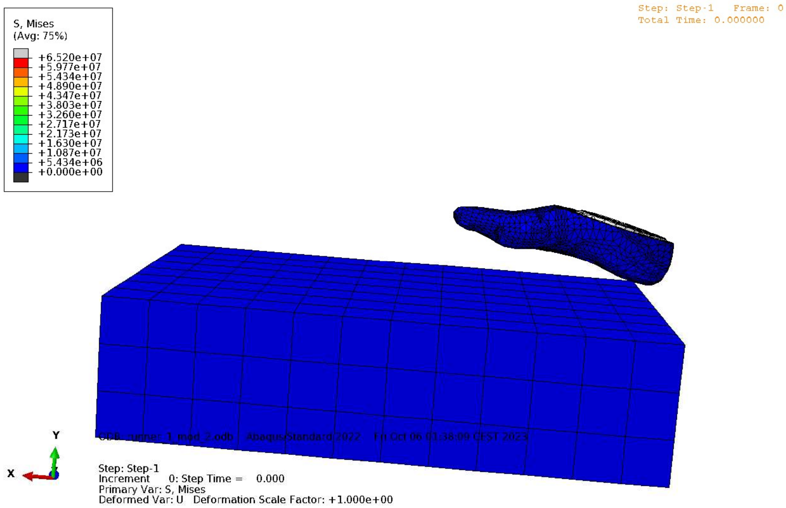


Midsole Prototype



Next step:

Model & simulate the adaptation of the runner to changes of the ground and the midsole.



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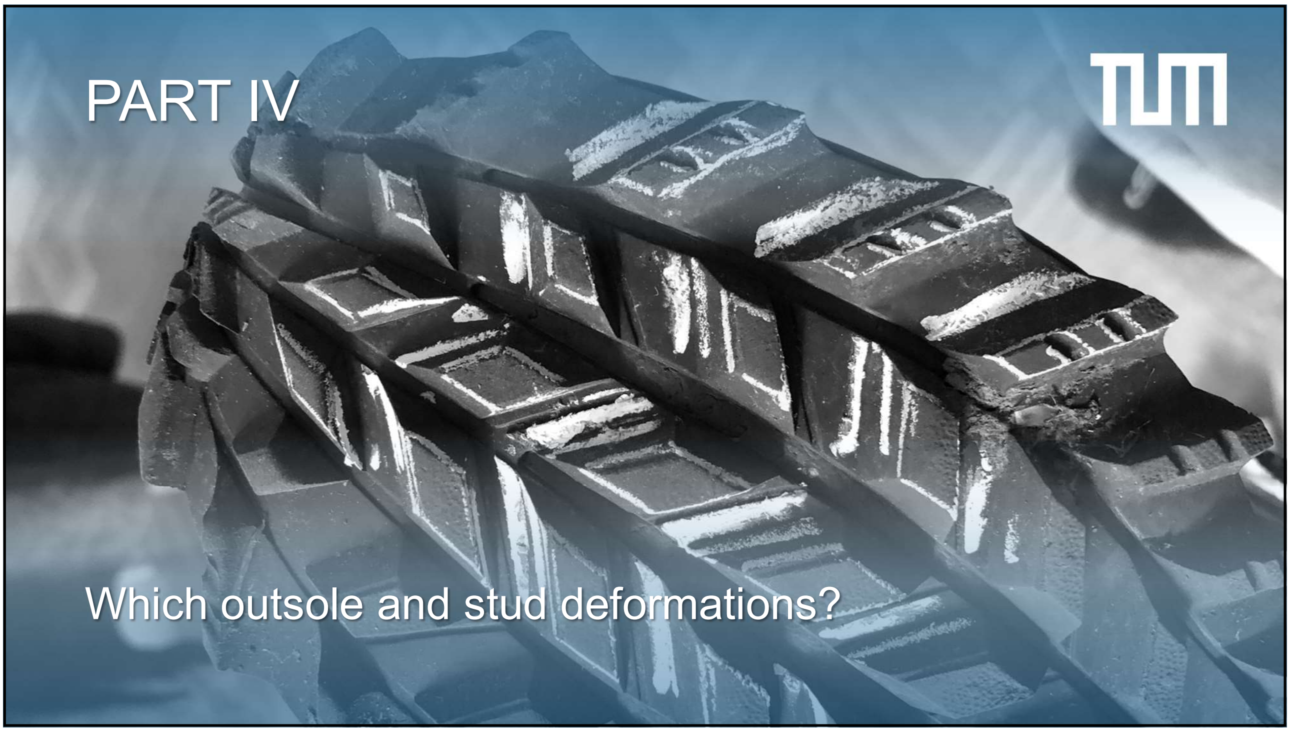
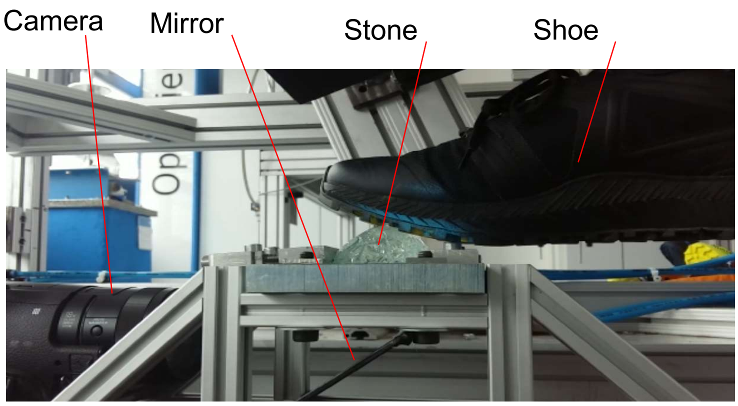


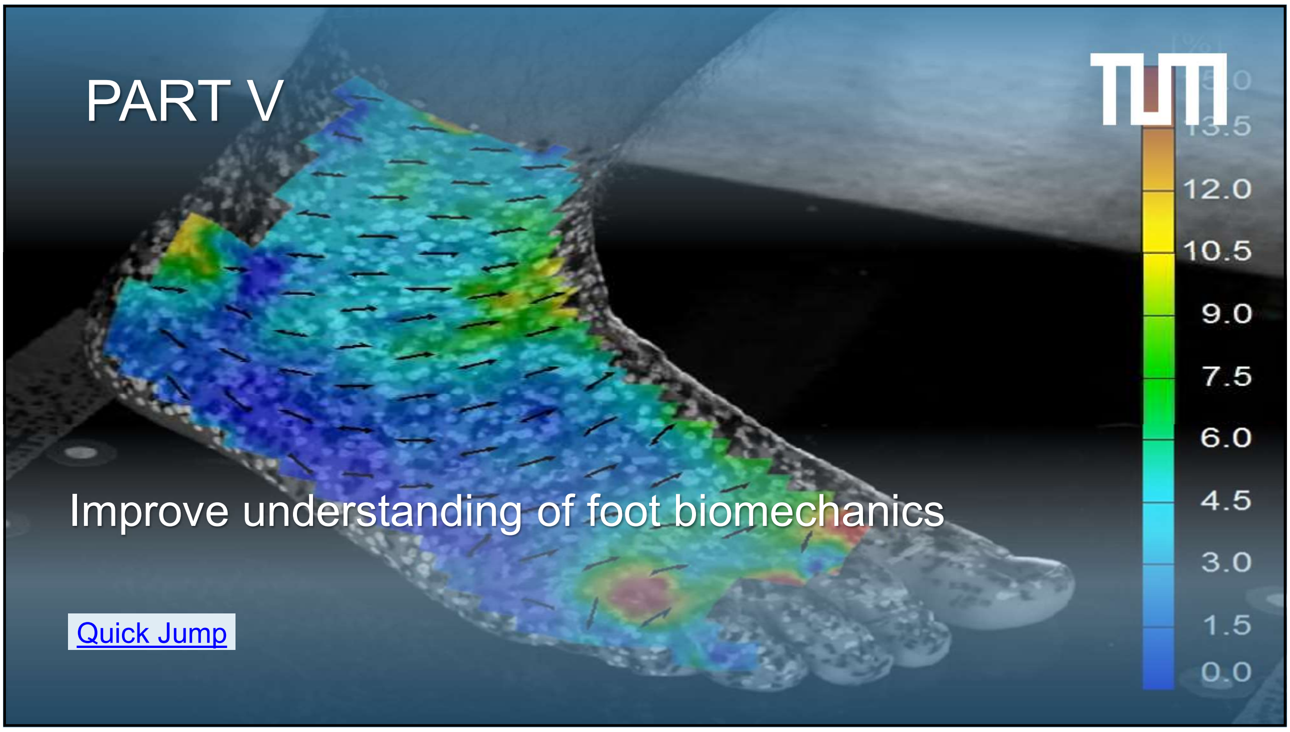
PART IV

Which outsole and stud deformations?

The glass-stone project



Let's have a look at the following 2-minutes video…



PART V

Improve understanding of foot biomechanics

[Quick Jump]

Objective

Develop and validate a passive multi-body model of the human foot

Mid-term application

How much energy is dissipated in the passive structures of the foot and how much is returned?

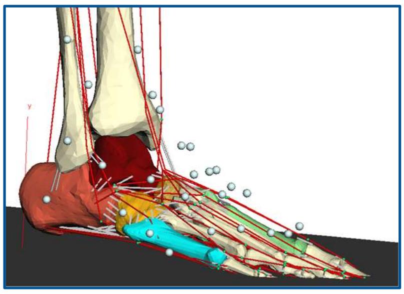
Long-term research goal

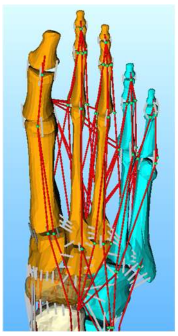
Derive a fatigue model for overuse injuries

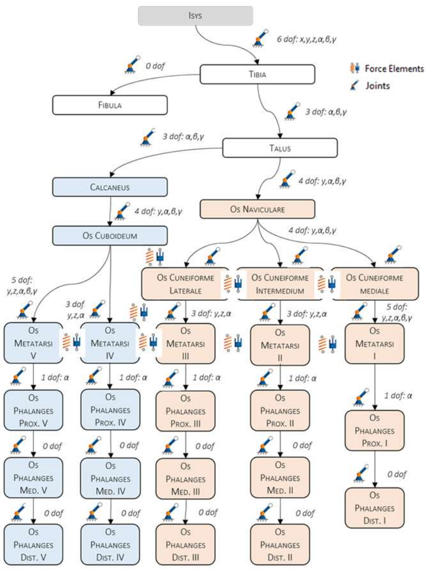
Anja KRAUTTER, M.Sc

Multibody foot model in Simpack®

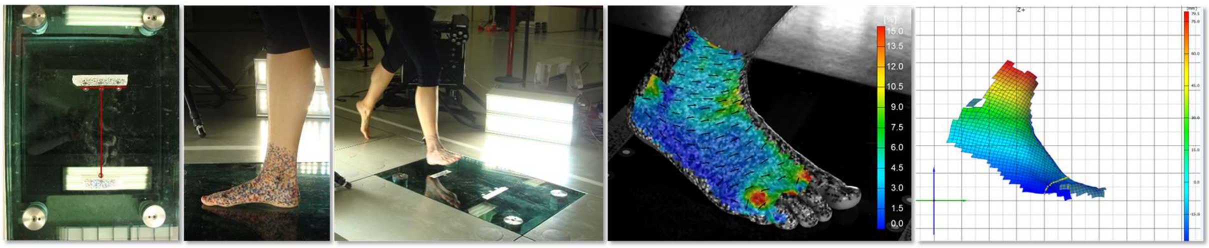
28 bones from CT-data, more than 100 visco-elastic ligaments, PE & SE elements of muscles. No active (CE) elements.





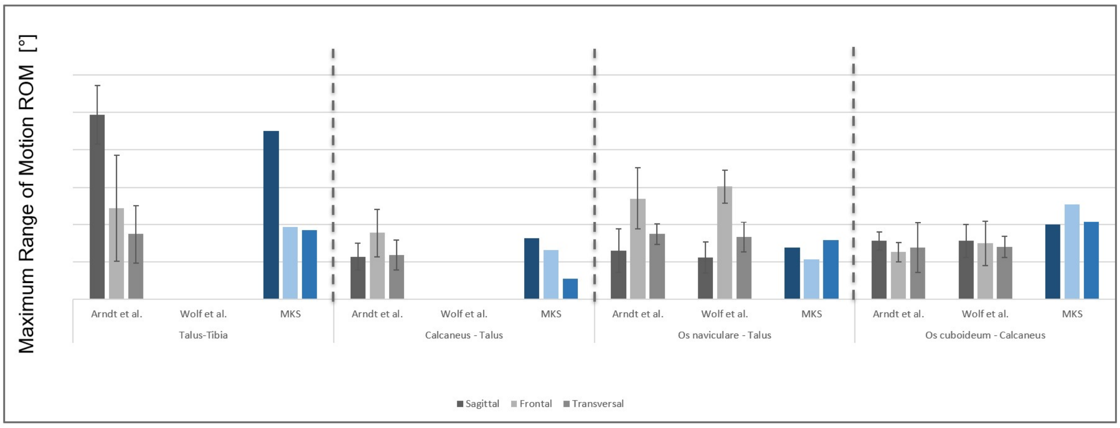


Data collection steps

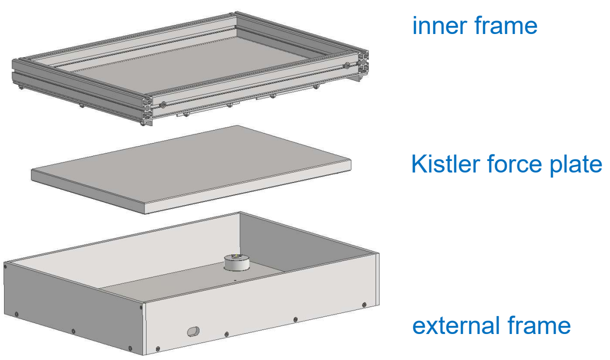


Defined coordinate system	Reference measurement neutral-zero	Barefoot running recorded from medial and lateral at f = 400Hz	Calculated relative surface deformation as calculated by ARAMIS (recording from lateral)	Joined („stitched“) view of surface deformation (lateral + medial values combined)

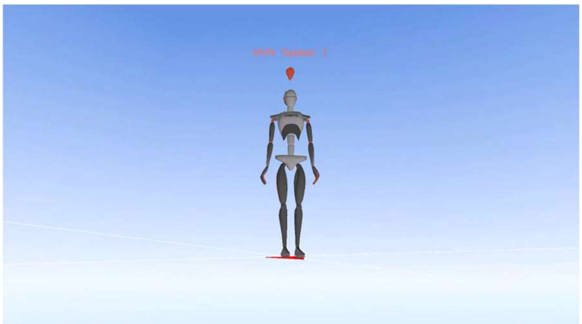
Comparison with in-vivo studies (Arndt et al. (2007) and Wolf et al. (2008))



Inclined force plate covered with soil or stone

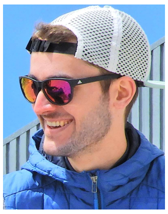


3D-kinematics, GRF and EMG - on inclined forest soil

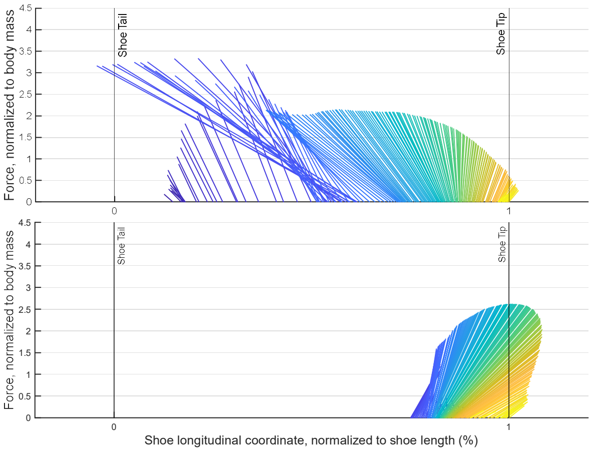


Details at foot strike

Resulting vector of ground reaction force and its location on the running shoe



Valentin WOHLGUT, M.Sc.
valentin.wohlgut@tum.de



Downhill

- Higher normal GRF during downhill running
- Initial contact in the rearfoot area of the foot
- Primarily braking forces

Uphill

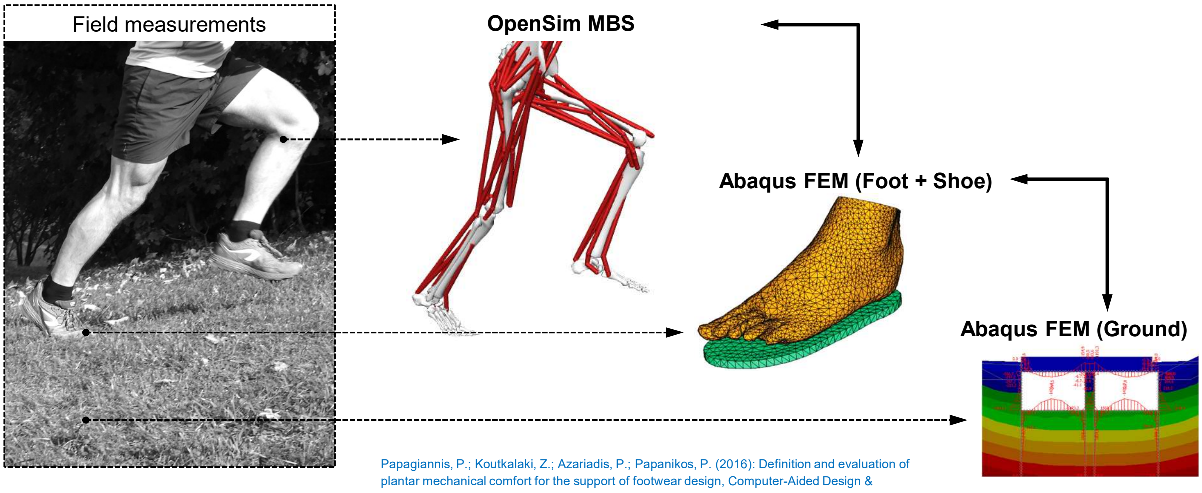
- Anterior shift of the foot contact during uphill running
- Almost no braking forces, ‘propulsive character‘

EMG, GRF and plantar pressure - on inclined rocky surface

insole pressure

force plate

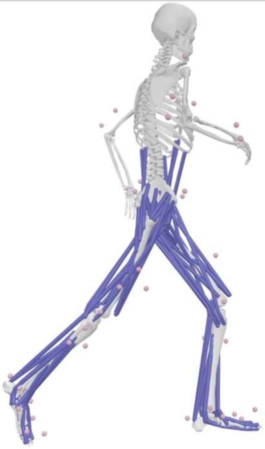
Simulation: Coupled MBS-FEM-Simulations

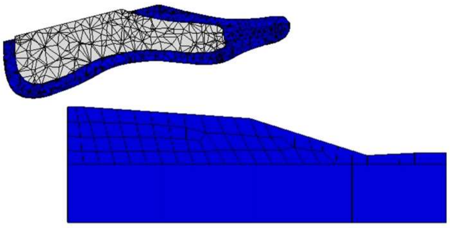


Papagiannis, P.; Koutkalaki, Z.; Azariadis, P.; Papanikos, P. (2016): Definition and evaluation of plantar mechanical comfort for the support of footwear design, Computer-Aided Design & Application, Vol. 13, No. 2, 162–172. https://www.finesoftware.de/geotechnische-software/fem/

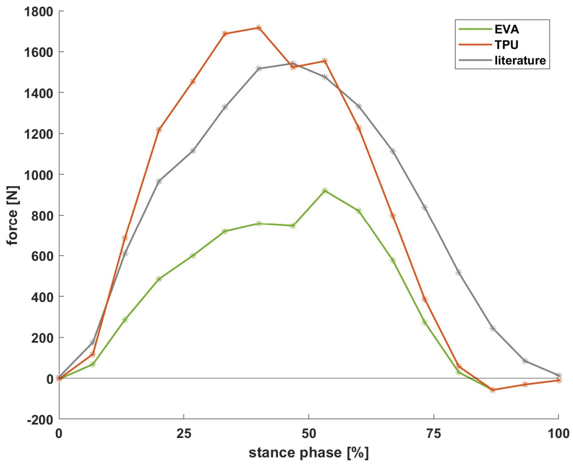
Co-Simulation MBS-FEM

Lea SPIERER, M.Sc.
lea.spierer@tum.de





Vertical component of ankle joint force



Soft floor material	Young's Modulus
thermoplastic polyurethane (TPU)	3 MPa [7]
ethylene vinyl acetate (EVA)	1 MPa [7]

[7] Li et al. (2019)

PART VII

Improve the knowledge regarding foot & knee injury mechanisms

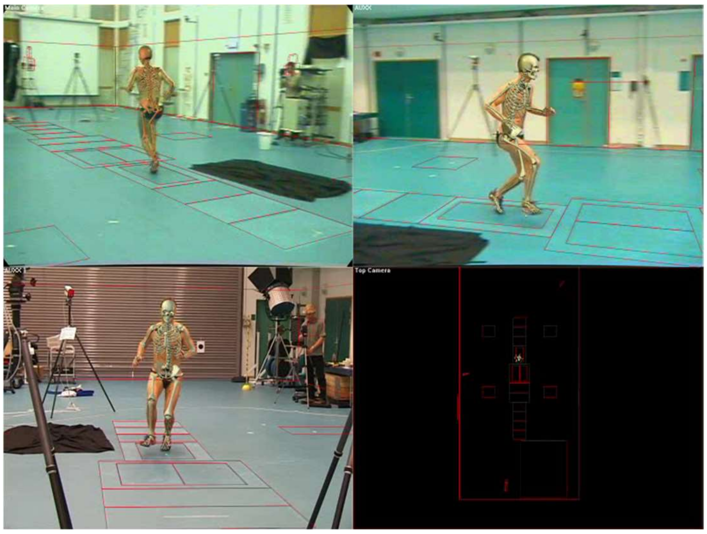
Mike Owen World Championship 2006

non-contact ACL rupture

3D-motion reconstruction by multi-angle fitting process

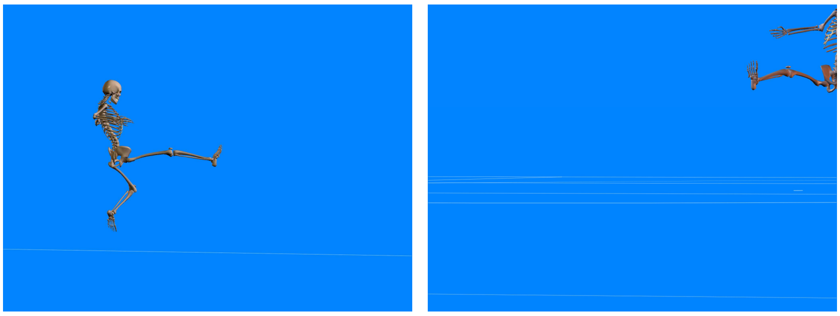
Krosshaug, T. & Bahr R. (2005) A Model-based image-matching technique for three-dimensional reconstruction of human motion from uncalibrated video sequences. JoB., 38, 919-29.

„Poser Method“
validation process

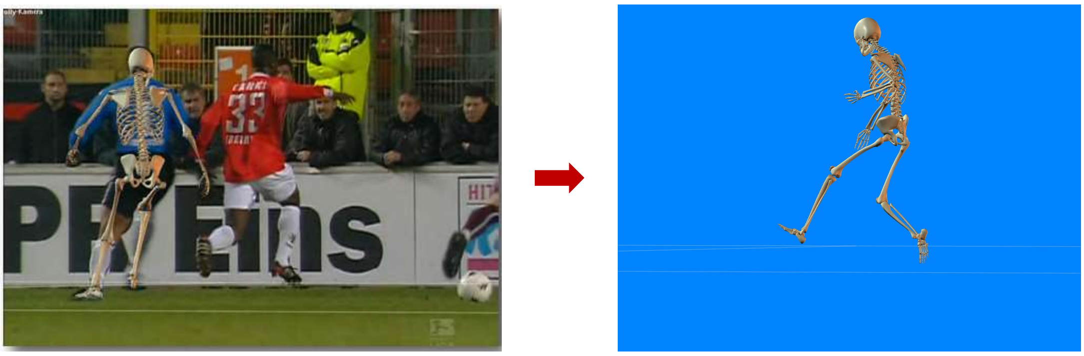


Video source: Krosshaug

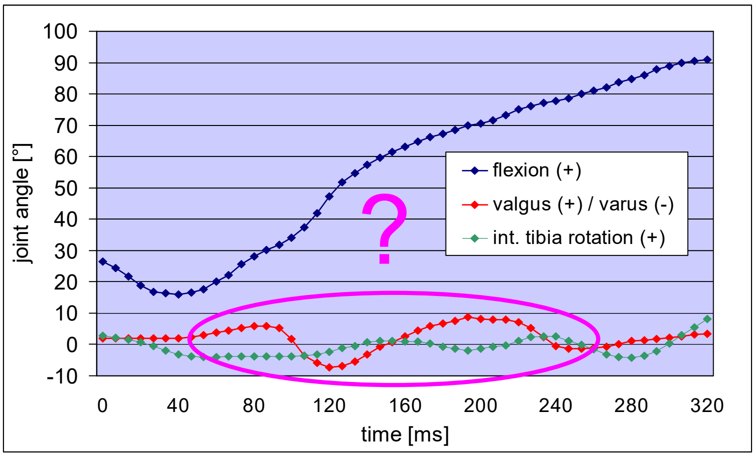
Example 1:
Van der Gun
(Sept. 2005)



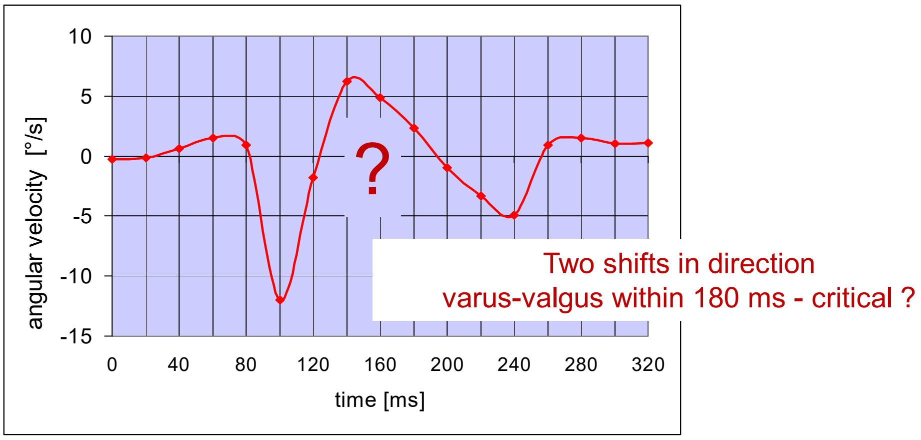
Example 2:
Tim Wiese (Juli 2005)

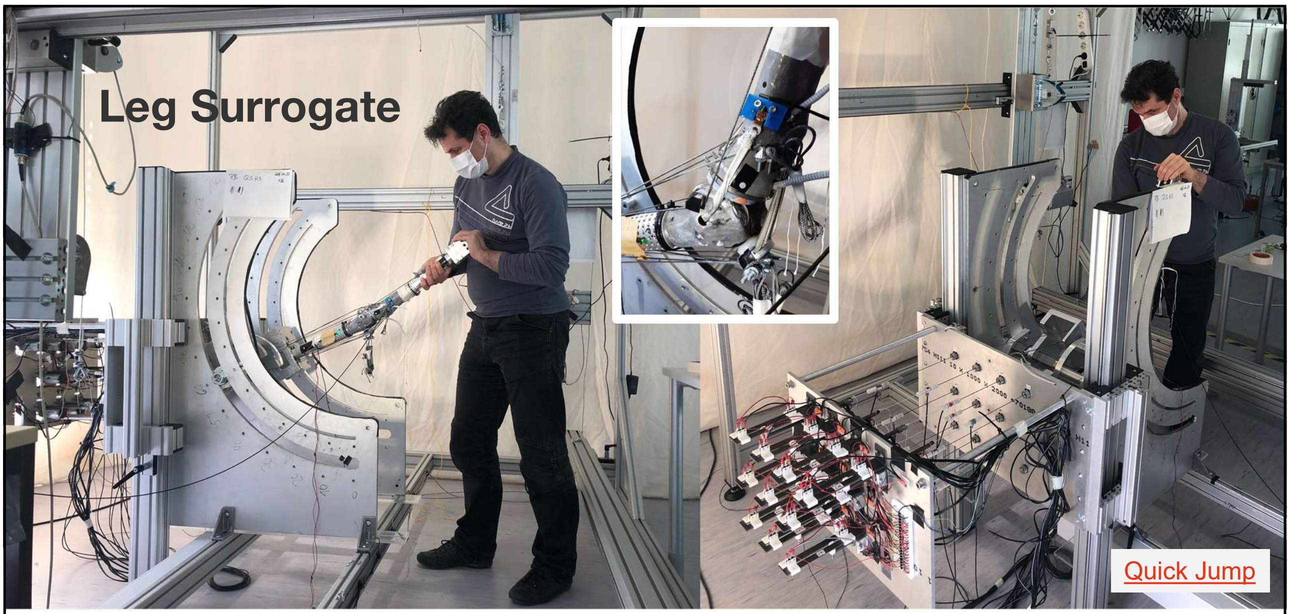


Reconstructed knee angles for the accident of Tim Wiese



Calculated knee joint angular velocity of Tim Wiese





Nusser, Hermann and Senner (2016)
Hermann, Jung, Grün, Brucker & Senner (2022)

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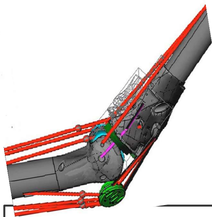
Principle Approach

replication of surrogate studies



1. Development of — Leg Surrogate → Multi-Body-Simulation

Markolf et al. 2004; Wascher et al. 1993

2. Validation — Quantitative data from human specimen tests

replication of studies of Markolf et al. (1990 & 2004)

3. Simulations of scenarios for which no quantified data is reported

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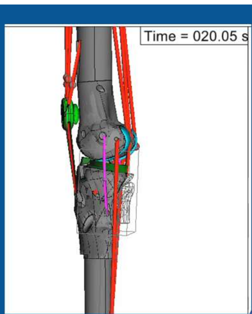
Simulated configurations

Studies using a digital Multi-Body-Model of the knee surrogate:

Manipulation of

Combinations	
muscle activation	5 Quad/Ham ratios
knee flexion angle	0-135°
internal | (external) torque	0-70 Nm
varus | valgus moment	0-40 Nm
anterior | posterior force on tibia head	0 | 100 N
axial compressive force	10 | 100 N

to ‘simulate’ ACL tensile force.



Multi Body Simulation Model

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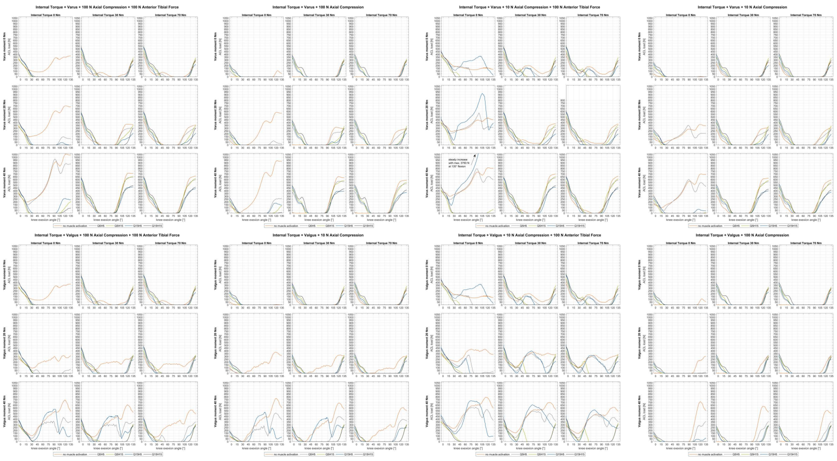
Results - Quantitative

200+ test scenarios



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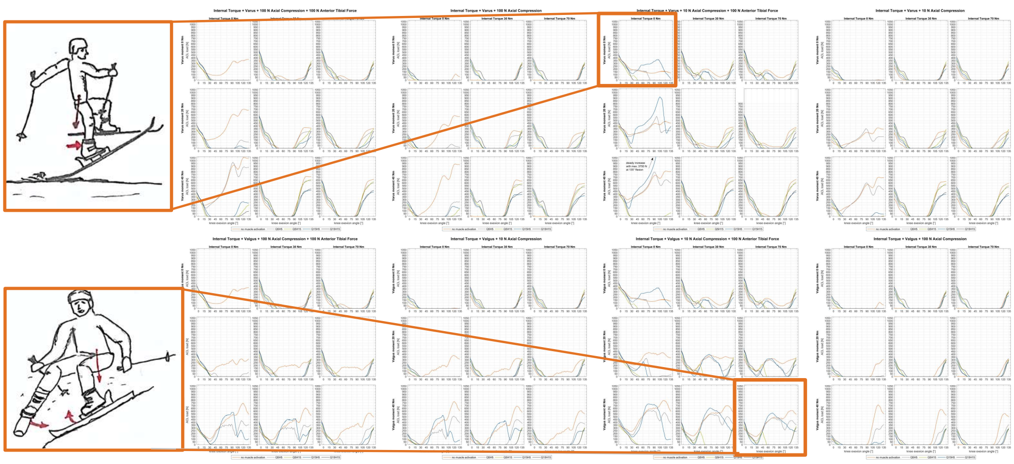
Two well familiar skiing injury situations

BIAD
Anterior tibial shift + Straight leg or deep flexion

Phantom Foot
Flexion + internal rotation + valgus



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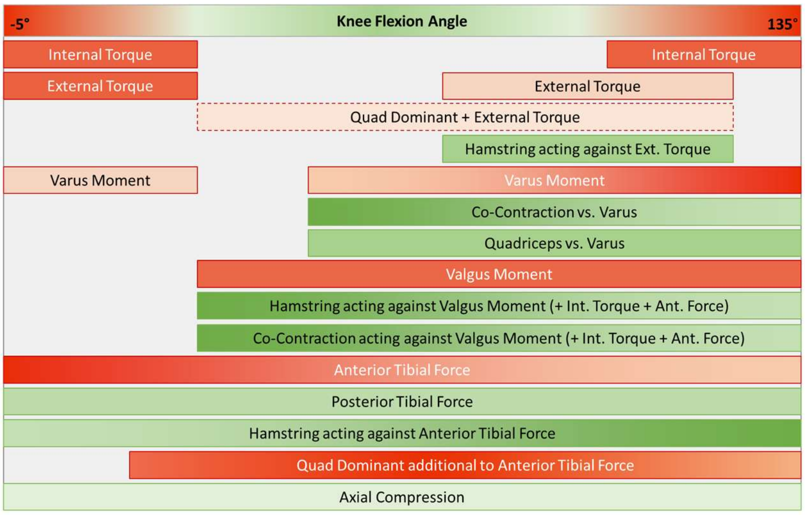
Key Results Qualitative

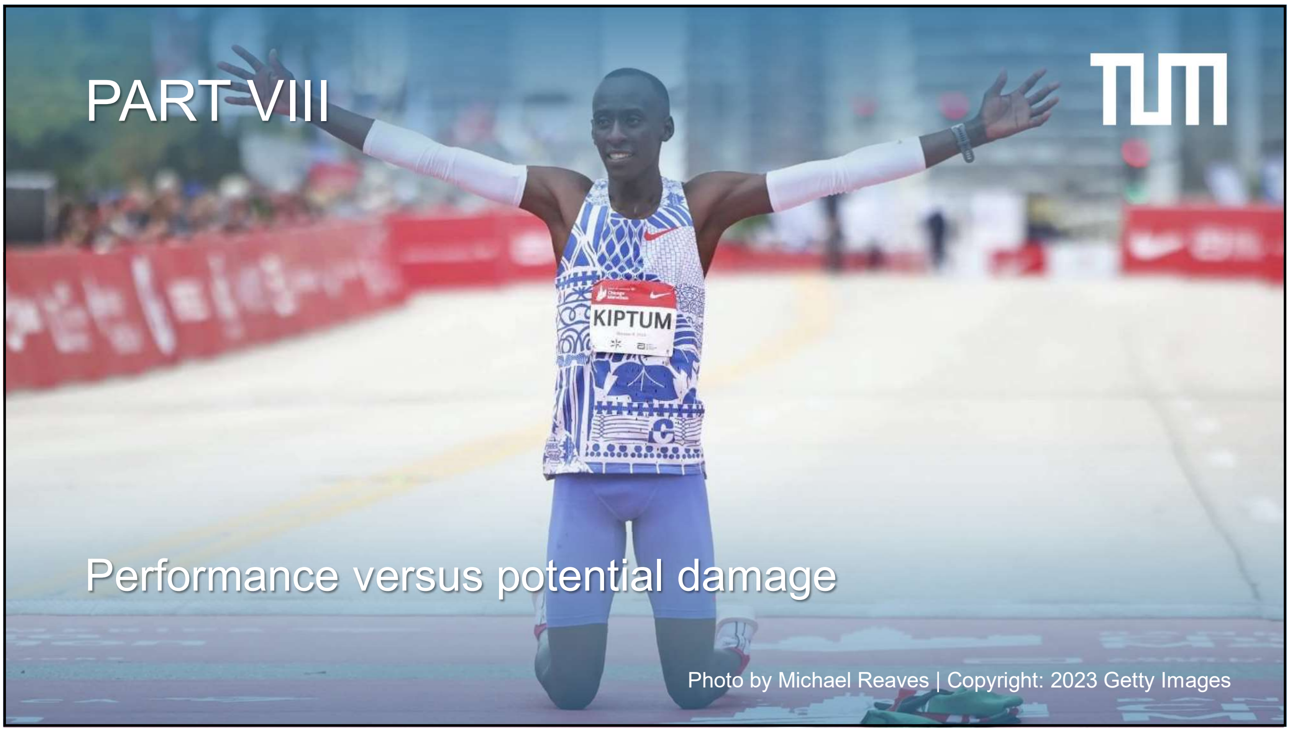
Generalized scheme on the effects of various parameters on ACL loading over the knee flexion range from 0 to 135°.

Red: negative effect;
Green: positive effect;

light to dark colouring: weak to strong effect.

Note:
The results for external torque higher than 5 Nm have not yet been included.



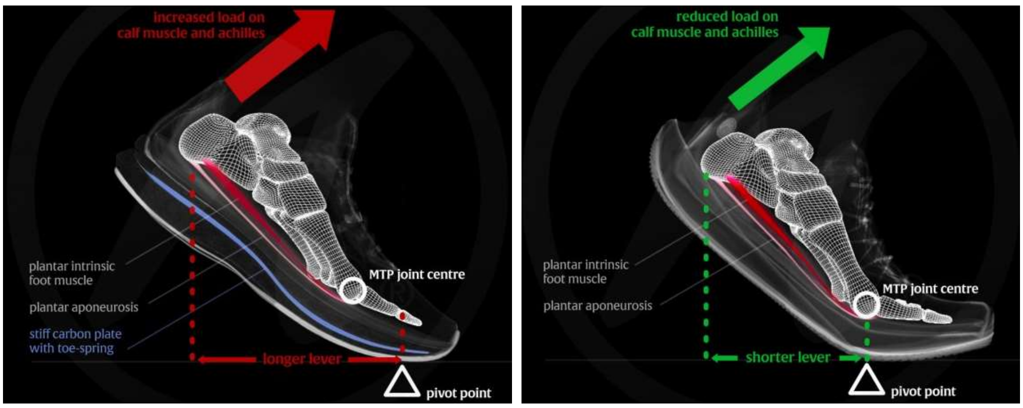


Construction of a „Carbon“ Running Shoe

- A carbon fibre composite plate is embedded into the midsole.
- Midsole higher than with conventional shoes.
- Material softer but with more energy return (87%) compared to PU (76%) or EVA (65%)

https://www.sports-insider.de/carbon-laufschuhe-im-vergleich-asics-nike-adidas-hoka-one-one-saucony-brooks-new-balance-und-die-alternativen-aus-dem-test-38676/

Changes to the foot‘s biomechanics



Source: https://www.joe-nimble.com/de/carbonfree

Reported increase of navicular *Type III* stress fractures

MRI

CT

Tenforde, A.; Hoenig, T.; Saxena, A.; Hollander, K. (2023). Bone Stress Injuries in Runners Using Carbon Fiber Plate Footwear. Sports Medicine.

Reaction of *World Athletics* (World Athletics (2021): Athletic Shoe Regulations, Book C – C2.1A)

"… these Regulations seek to balance the following principles:
[…] **fairness** within the sport of Athletics;
[…] **measures that support health & safety** (including injury prevention) of Athletes upon whom high levels of physical and mental demands are placed;
[…] performances (including records) in Athletics are achieved through the **primacy of human endeavour over technology** in Athletic Shoes and advances in the same (e.g. to allow for meaningful competition); and
[…] acknowledging that **Athletes wish to compete in 'high quality', 'innovative' and 'leading' Athletic Shoes**."

http://sport.orf.at/static/images/site/sport/20130939/marathon_berlin_weltrekord_start_body_a.2239741.jpg

Technical University of Munich
TUM School of Engineering and Design
Professorship Sport Equipment and Materials

Simplified take home message

Researching and engineering the interaction between human and environment needs more than off-the-shelf gait- & running analysis.

Thank you for listening & thank you Joaquim for having invited me.

TECHNICAL UNIVERSITY OF MUNICH
TUM School of Engineering and Design
Sport Equipment and Materials
Boltzmannstr. 15
D-85747 Garching
Tel.: +49-89-289-15366

https://www.mec.ed.tum.de/en/spgm/homepage/