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Diagnosis, Treatment and Rehabilitation: Biomechanics and Motor Control of Human Movement as the Links between Engineering Principles and Medical Arts

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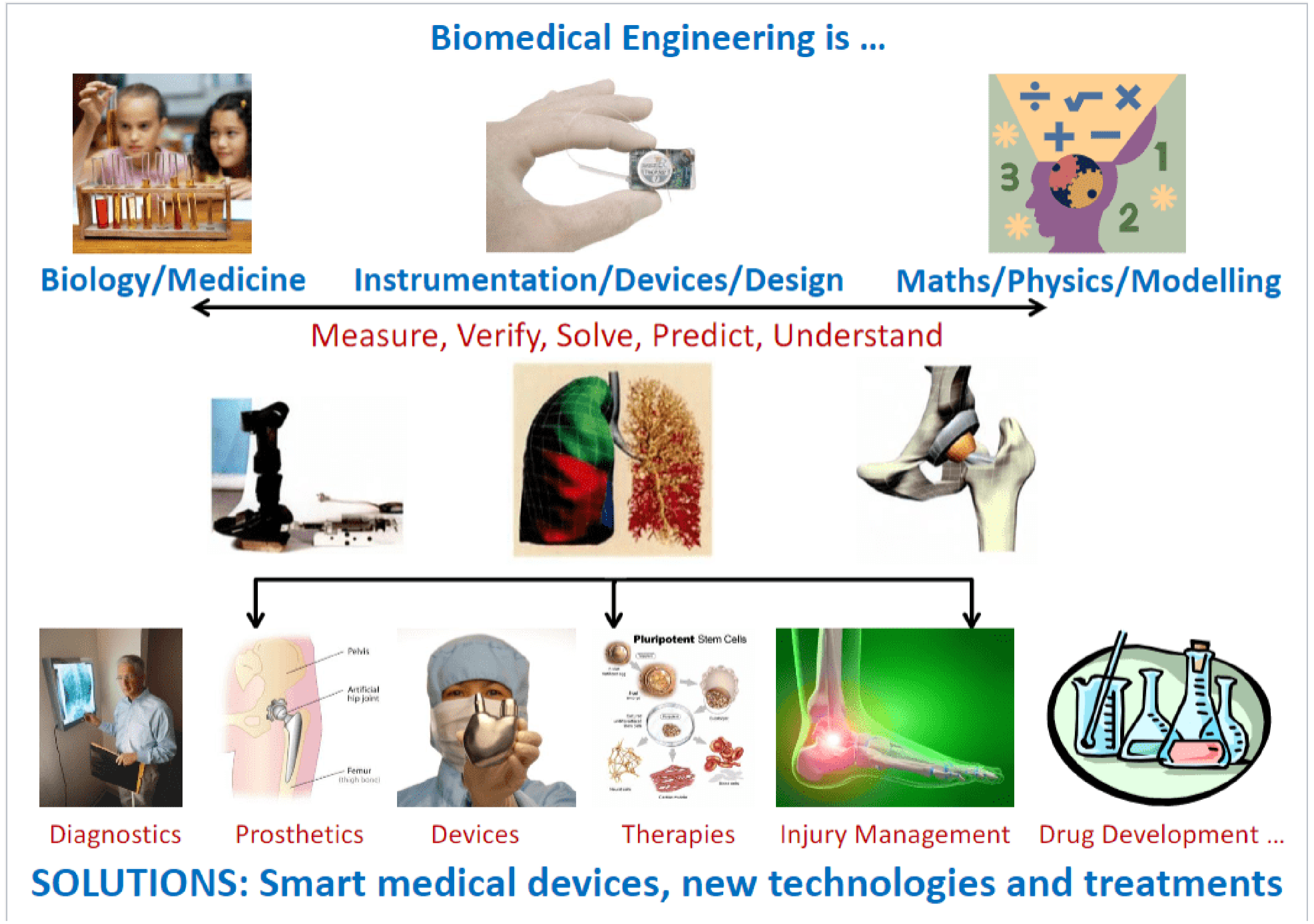
Outline

- What is Biomedical Engineering?
- Biomechanics and Motor Control of Human Movement
- Why Do We Need to Perform Human Movement Analysis?
- Study 1: How does cell phone usage while walking affect stability and variability of gait in young adults?
- Study 2: Biomechanical differences between healthy, osteoarthritic and post-operative medial stabilized knees
- Future directions

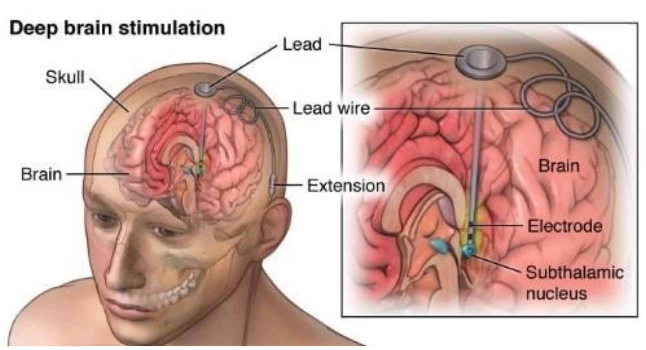
What is Biomedical Engineering?

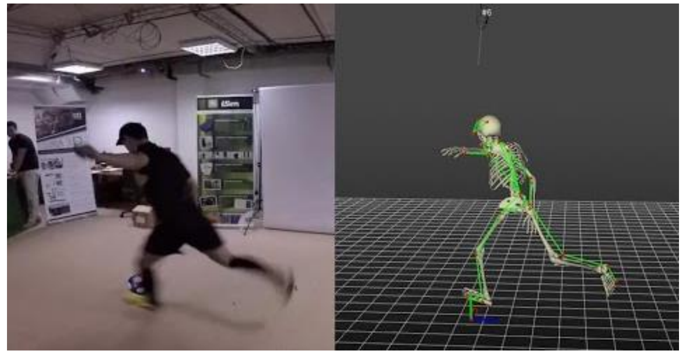
- Biomedical engineering, or bioengineering, is the application of engineering principles to the fields of biology and health care.

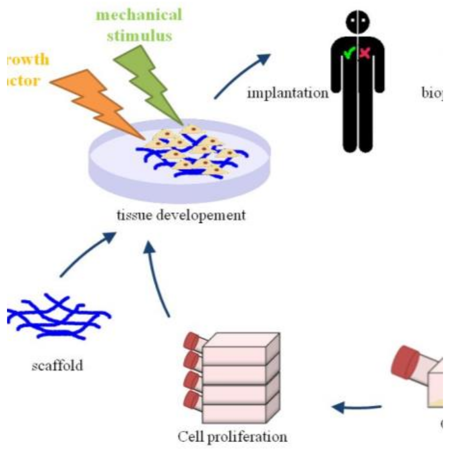
- Bioengineers work with doctors, therapists and researchers to develop systems, equipment and devices in order to solve clinical problems.

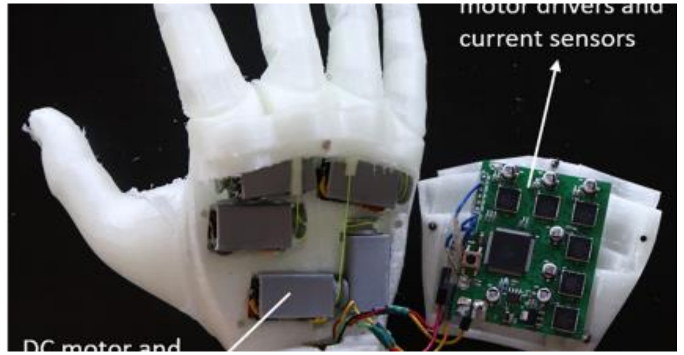


What is Biomedical Engineering?





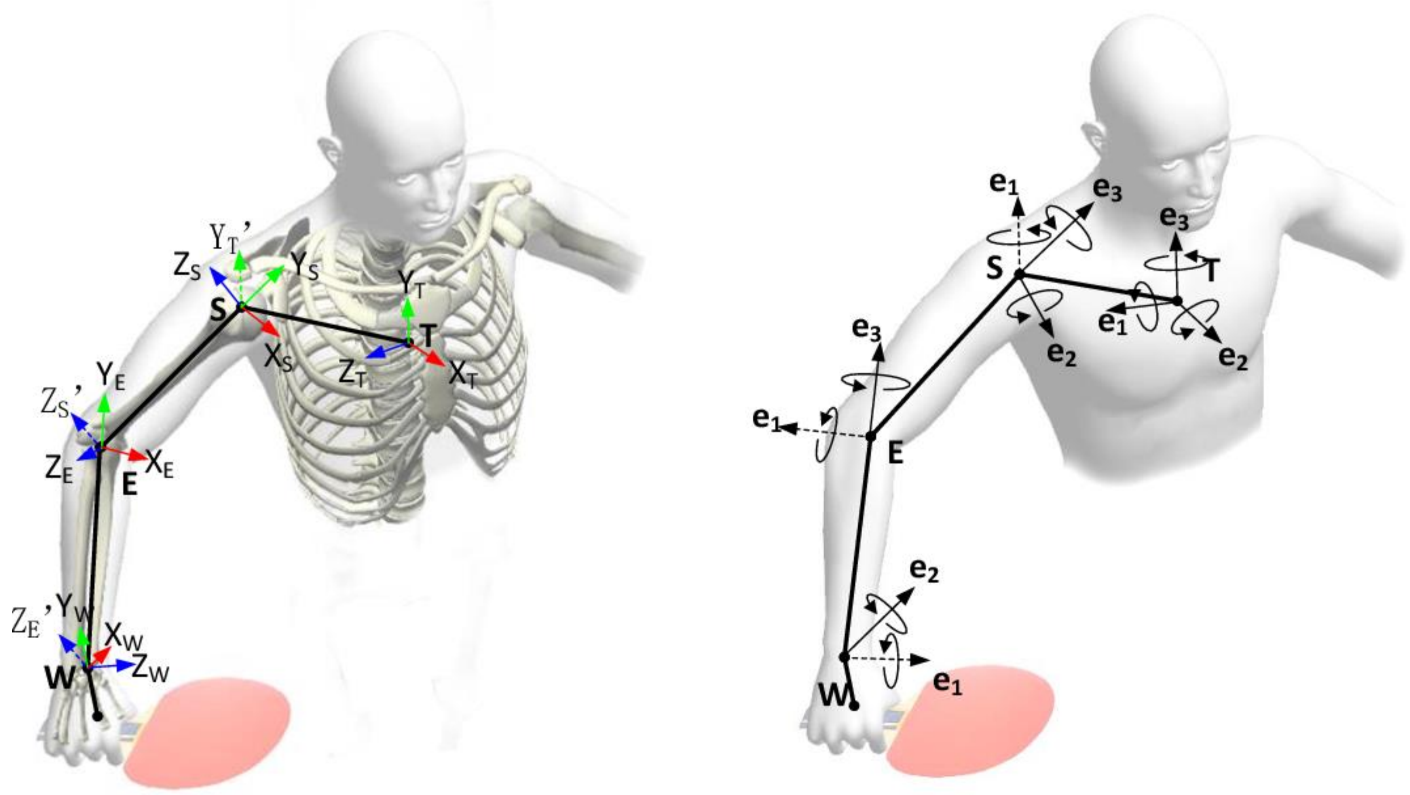




- Bioelectric
- Biomechanics
- Biomaterial
- Tissue Engineering
- Sports Engineering

- Biomechanics involves the use of the mechanical principles of physics and engineering to study human motion and the mechanical properties of biological tissues.

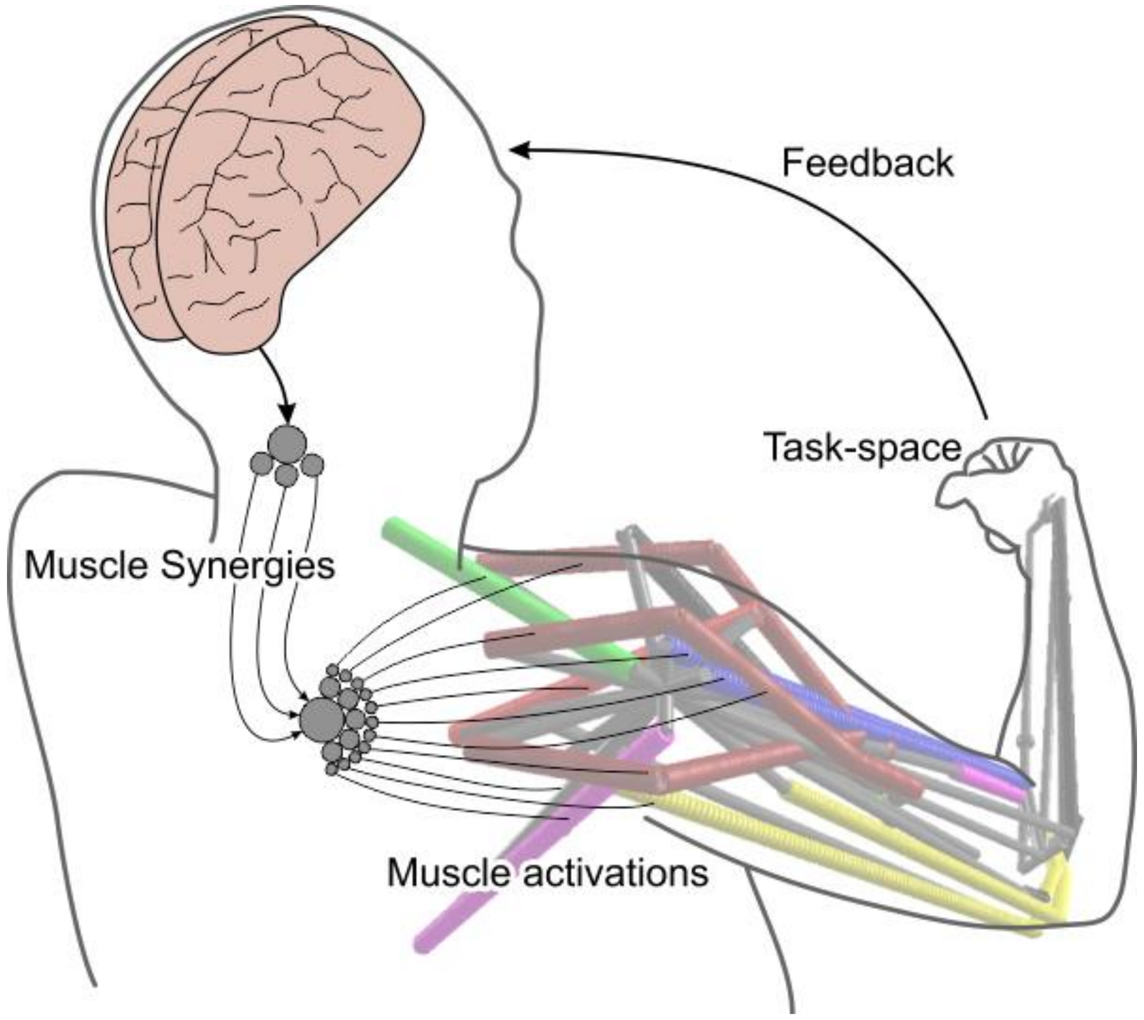
- Applications:
    - Sports biomechanics
    - Occupational biomechanics
    - Clinical biomechanics
    - Neuromechanics



Biomechanics and Motor Control of Human Movement

- Motor Control seeks to understand how movements of the human body are controlled and executed, and how motor skills develop through the lifespan and are acquired through practice.

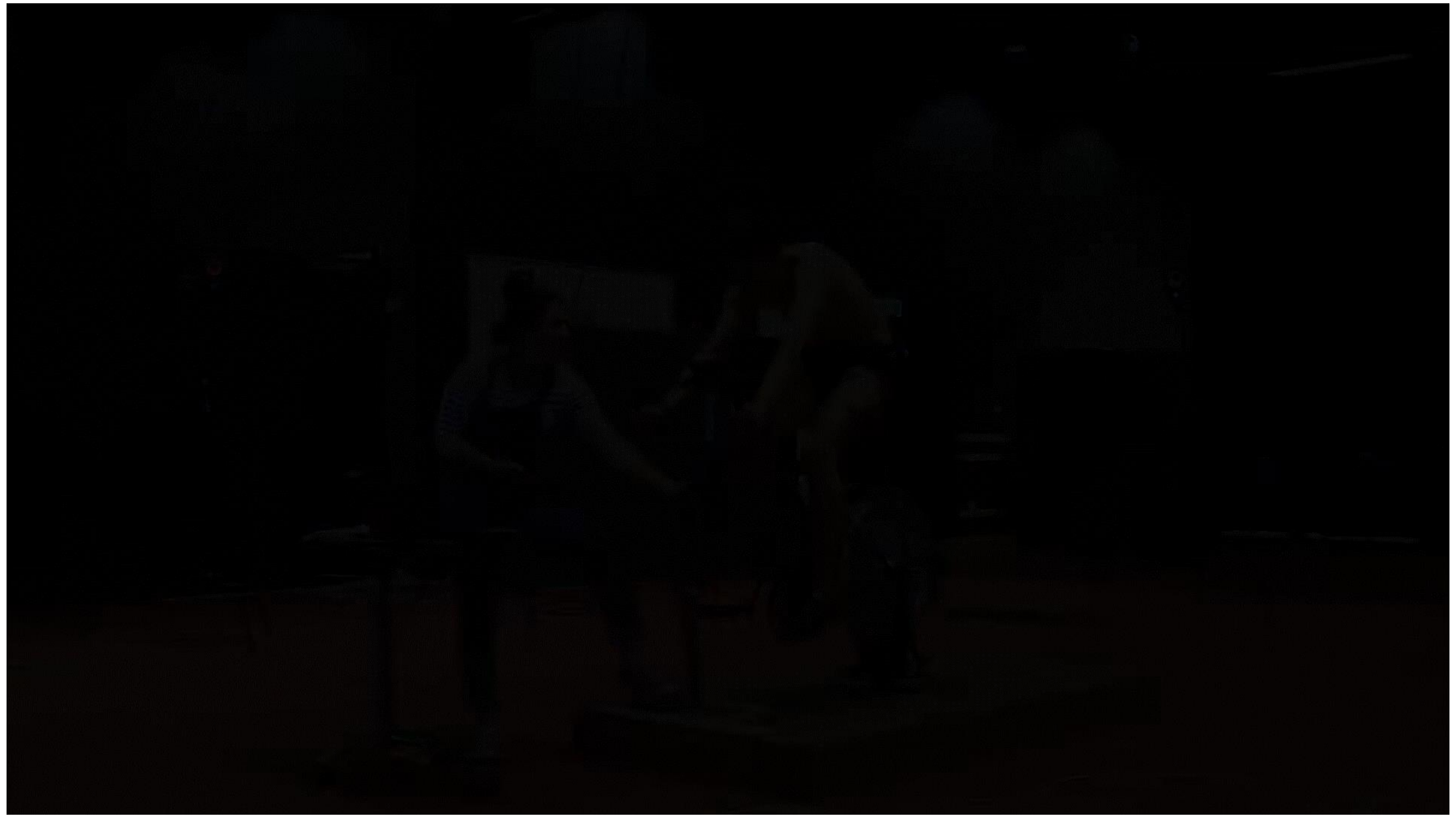
- This field employs approaches from neuroscience to cognitive science to examine skill acquisition, coordination and control in healthy people, but also how these processes are affected by factors such as injury, disability, disease, disuse and fatigue.



Why Do We Need to Perform Human Movement Analysis?

- Human motion analysis is the systematic study of human motion by careful observation, augmented by instrumentation for measuring body movements, body mechanics and the activity of the muscles.

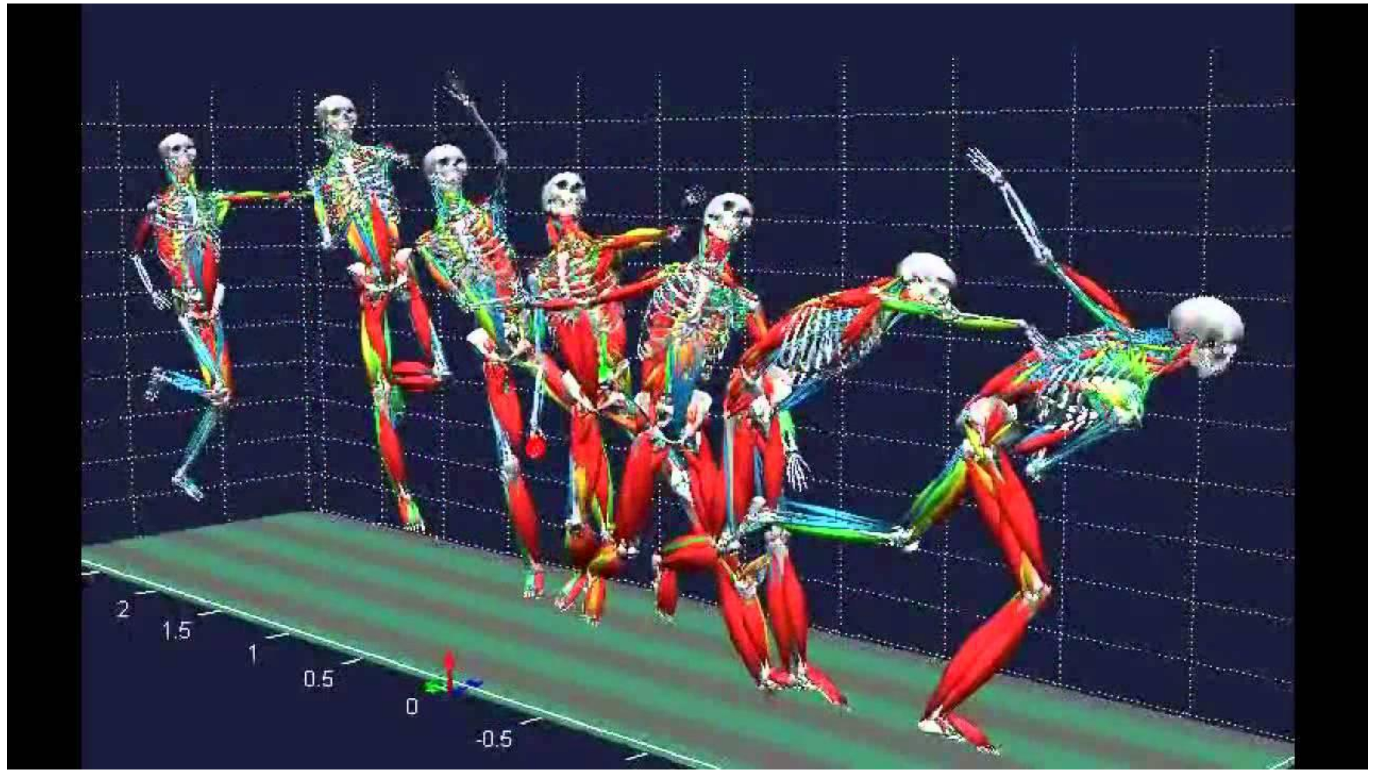
- It aims to gather quantitative information about the mechanics of the musculoskeletal system during the execution of a motor task.



Why Do We Need to Perform Human Movement Analysis?

- Human movement is achieved by a complex and highly coordinated mechanical interaction between bones, muscles, ligaments and joints within the musculoskeletal system under the control of the nervous system.

- Muscles generate tensile forces and apply moments at joints with short lever arms in order to provide static and dynamic stability of the body under gravitational and other loads while regularly performing precise limb control.



Why Do We Need to Perform Human Movement Analysis?

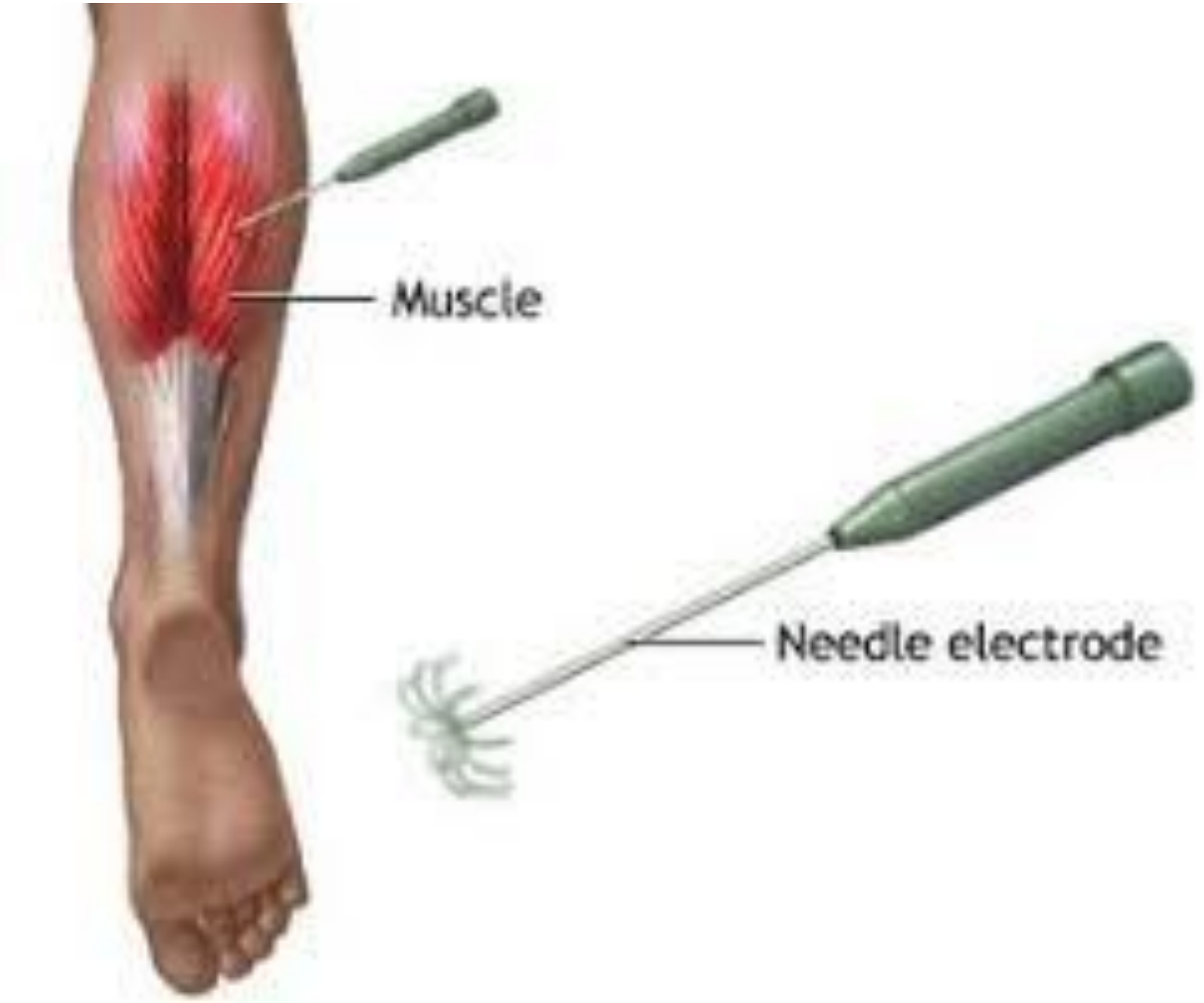
- Any injury or lesion of any of the individual elements of the musculoskeletal system will change the mechanical interaction and cause degradation, instability or disability of movement.

- On the other hand, proper modification, manipulation and control of the mechanical environment can help prevent injury, correct abnormality, and speed healing and rehabilitation.

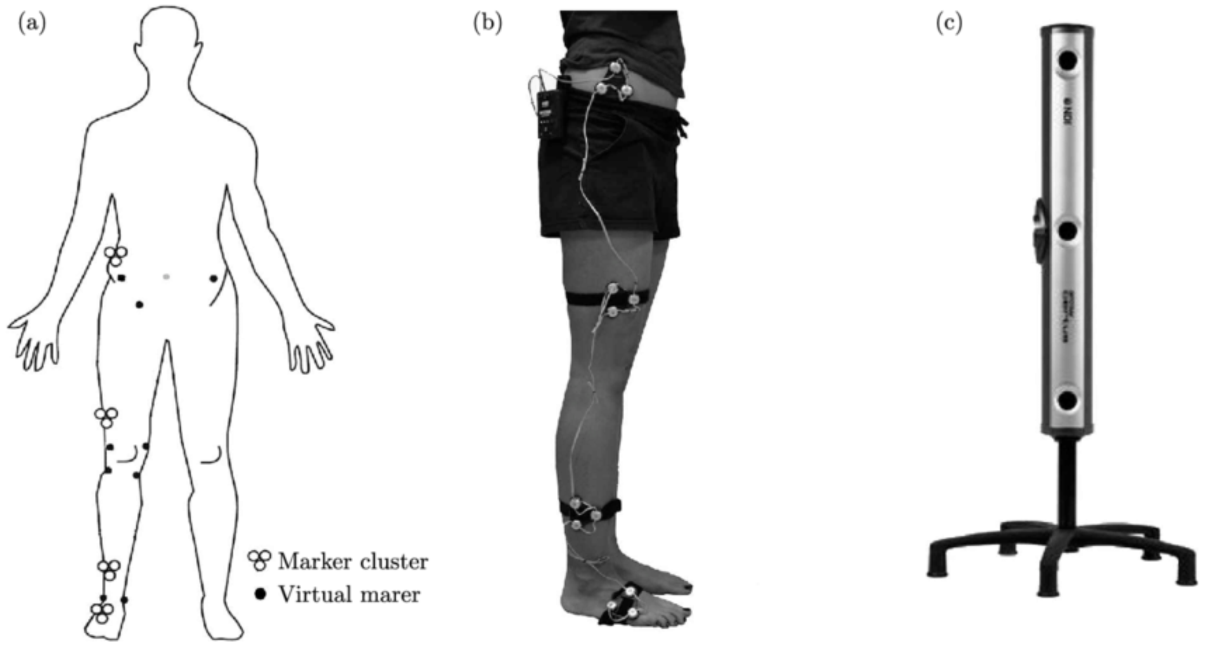
- Therefore, understanding the biomechanics and loading of each element is helpful for studying disease aetiology, making treatment decisions and evaluating the effects of treatment.

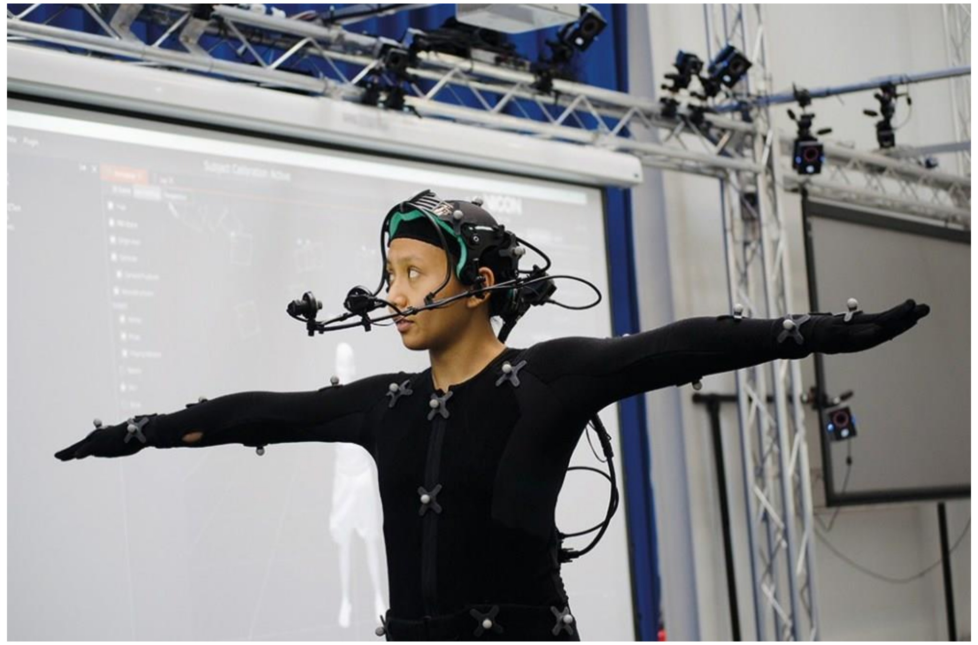
Why Do We Need to Perform Human Movement Analysis?

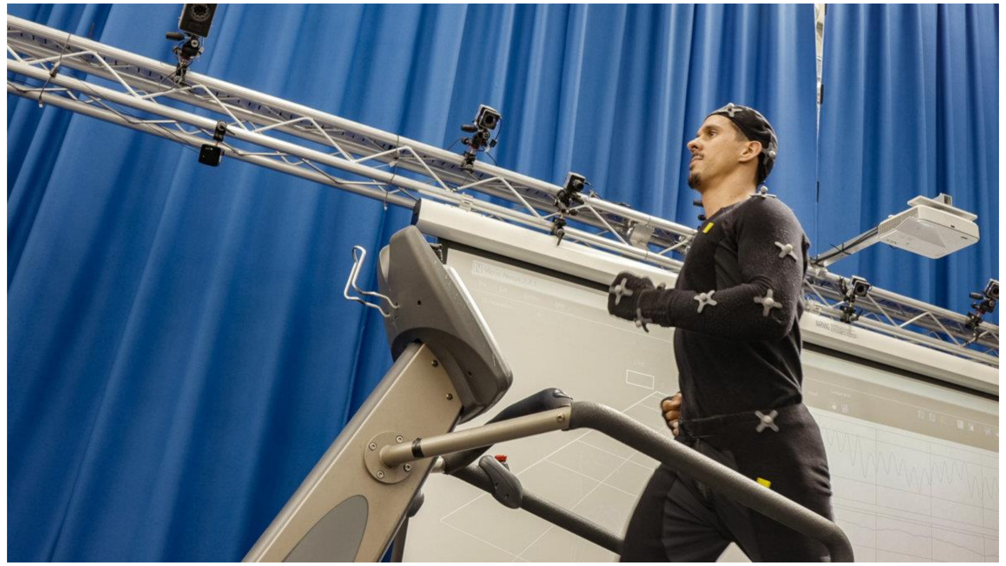
- However, because of ethical considerations and technological limitations, direct measurement of the forces transmitted in the human body is possible only in exceptional circumstances, such as through instrumented implants.



Why Do We Need to Perform Human Movement Analysis?







Study 1

- ***How does cell phone usage while walking affect stability and variability of gait in young adults?***

- Cognitive load associated with dual-tasking while walking is known to affect balance and increase fall risk. The objective of this study was to quantify the effect of cell phone usage on dynamic balance during walking.

Study 1

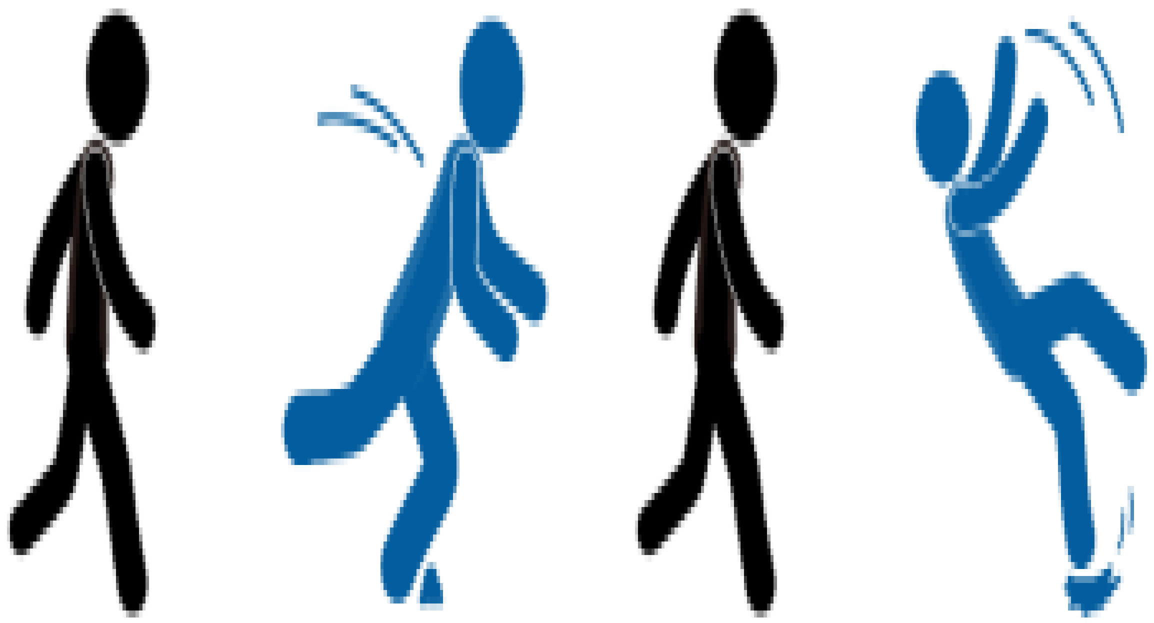
- **This research is focused on**:
  - The biomechanical consequences of dual-tasking due to cell phone usage during walking
  - The influence of internally applied perturbations on dynamic stability and risk of falling during walking
  - Investigation of the adopted strategies by individuals to maintain balance under different conditions
  - Highlighting the most destabilizing type of cell phone usage while walking

Study 1

- **Fall**: inadvertently coming to rest on the ground, floor or other lower level, excluding intentional change in position to rest in furniture, wall or other objects (Hauer et al., 2006).

- **Stability**: a system's response to perturbation, OR, the ability to resist a disruption of equilibrium (Sinitksi et al., 2012).

- Perturbation experiments have been used to elucidate the response of the nervous system during walking (Kang, 2007).

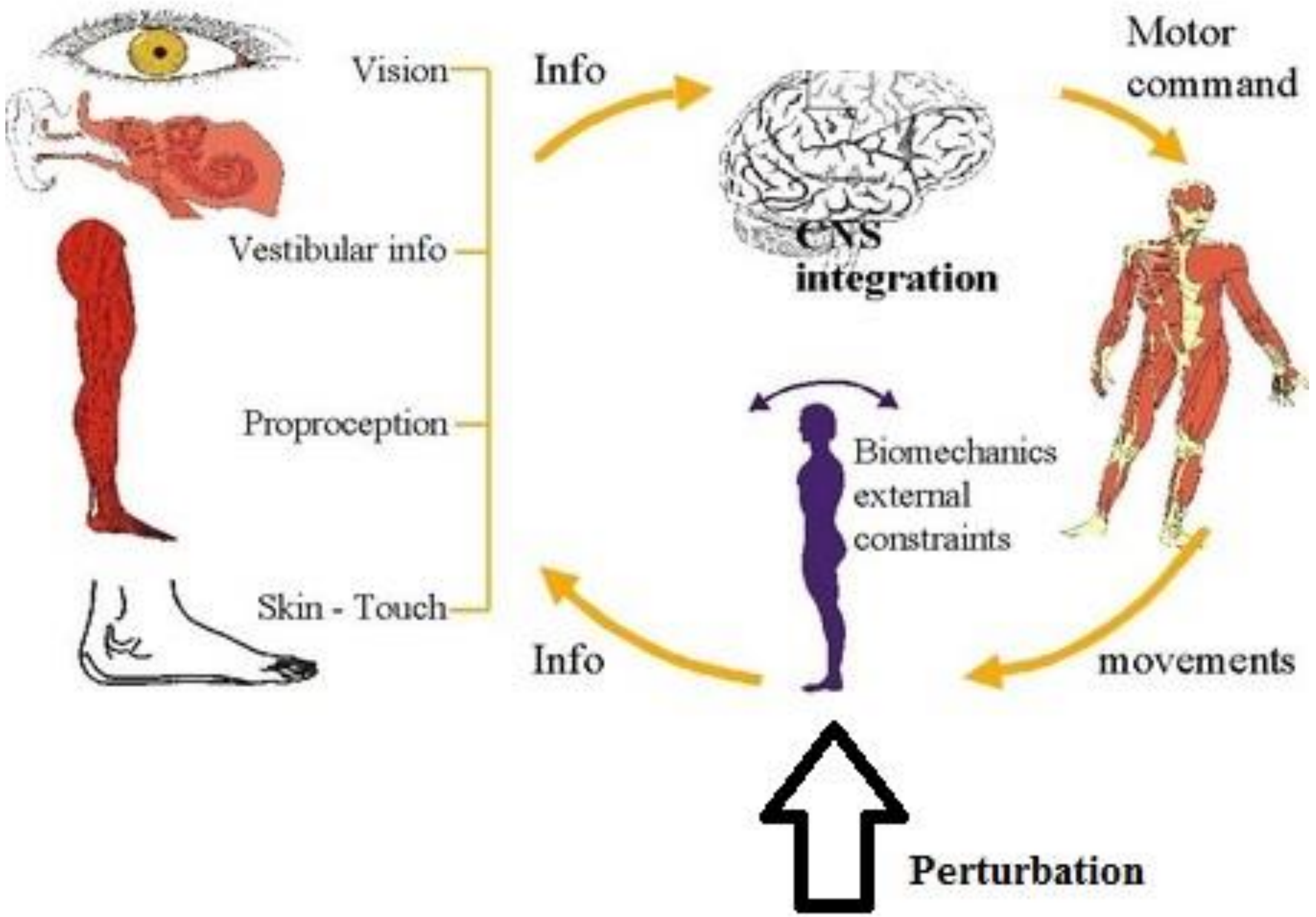


Study 1

- Different types of perturbation (Kang et al.,2007):
  - **Internal** e.g., neuromuscular noise due to dual-tasking during walking
  - **External** e.g., uneven walking surface or a slippery floor

Study 1

- How does the human body responds to perturbations?

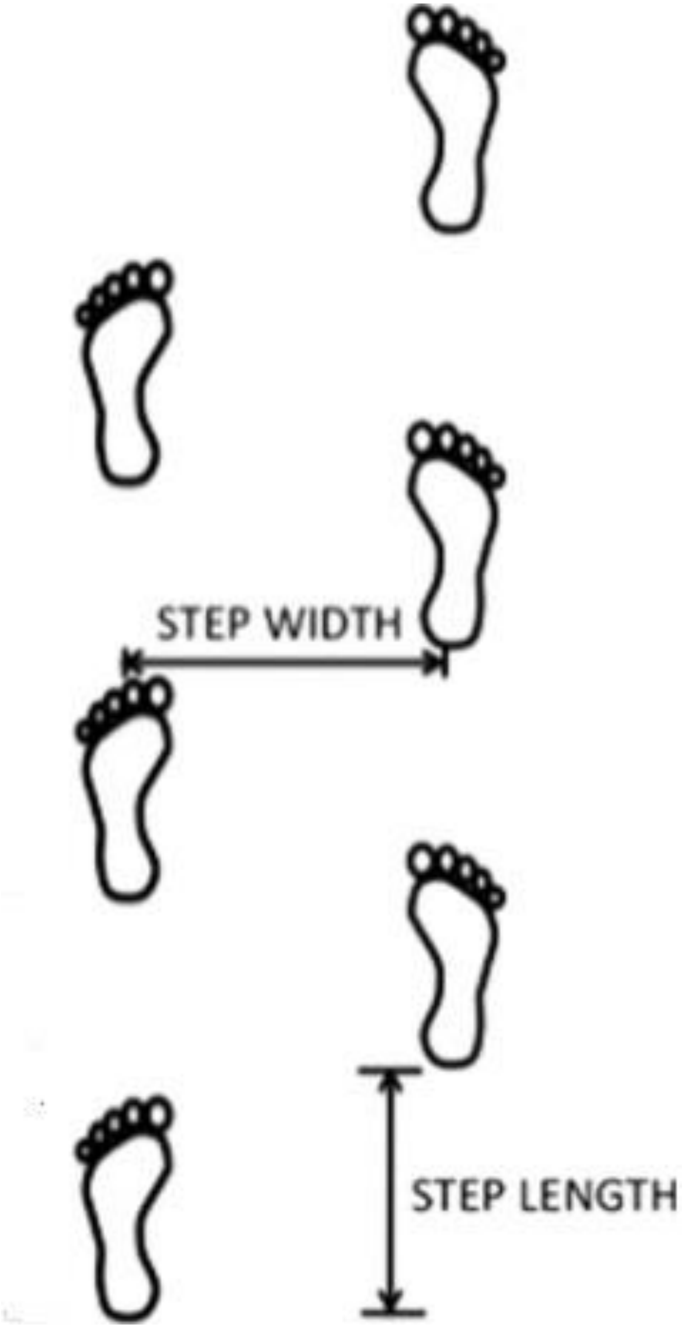


Study 1

- **Falling Risk Assessment**

– Risk of falling can be assessed by examining quantitative and variability of the following measures (Young et al., 2012):

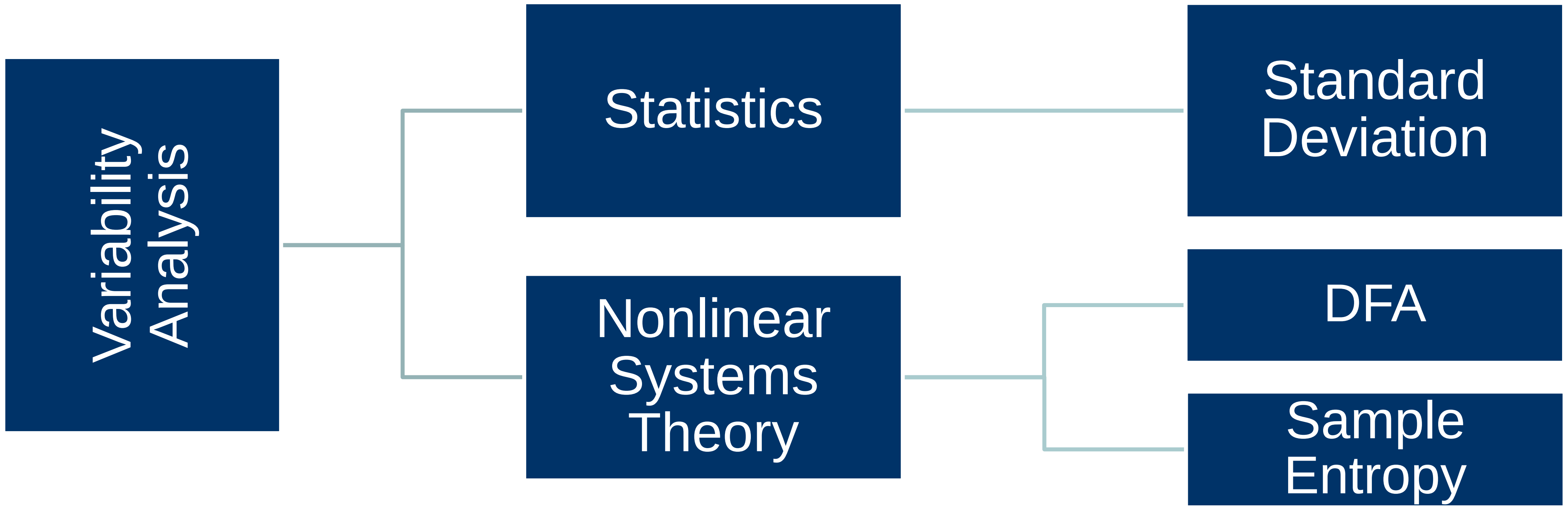
  - step width (SW)
  - step length (SL)
  - step time (ST)
  - and variability of these measures



Study 1

- **Variability**

  Typical variations that are present in motor performance and are observed across multiple repetitions of a task (Bruijn et al., 2013).



Study 1

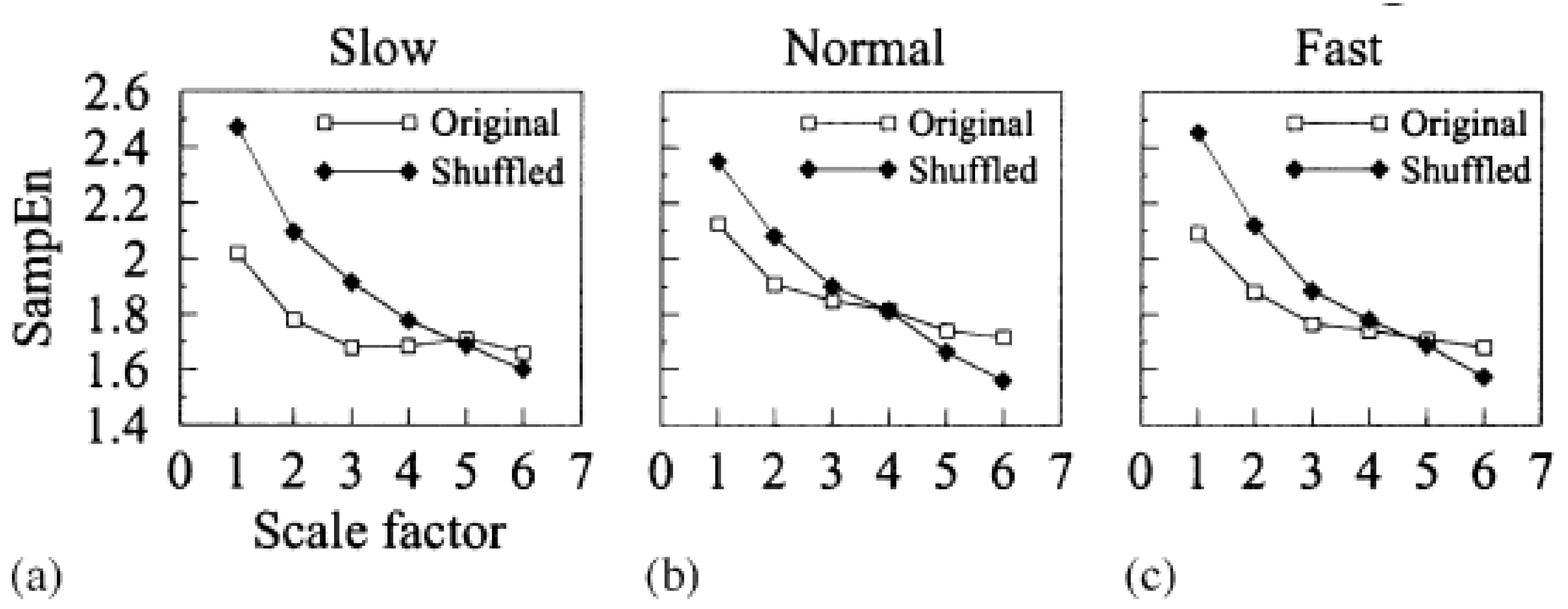
- Sample Entropy (SampEn) is an appropriate choice for regularity analysis.

$$S_m = (N-m)^{-1}\sum_{i=1}^{N-m} S_m(i)$$

$$S_m(i) = \frac{S_i}{N-m}$$

- By repeating the same procedure for
- $m+1$, T_m can be derived. SampEn can be measured as

$$\mathrm{SampEn} = \lim_{N\to\infty} \ln\left(\frac{S_m}{T_m}\right) \; or \; \ln\left(\frac{S_m}{T_m}\right)$$



Study 1

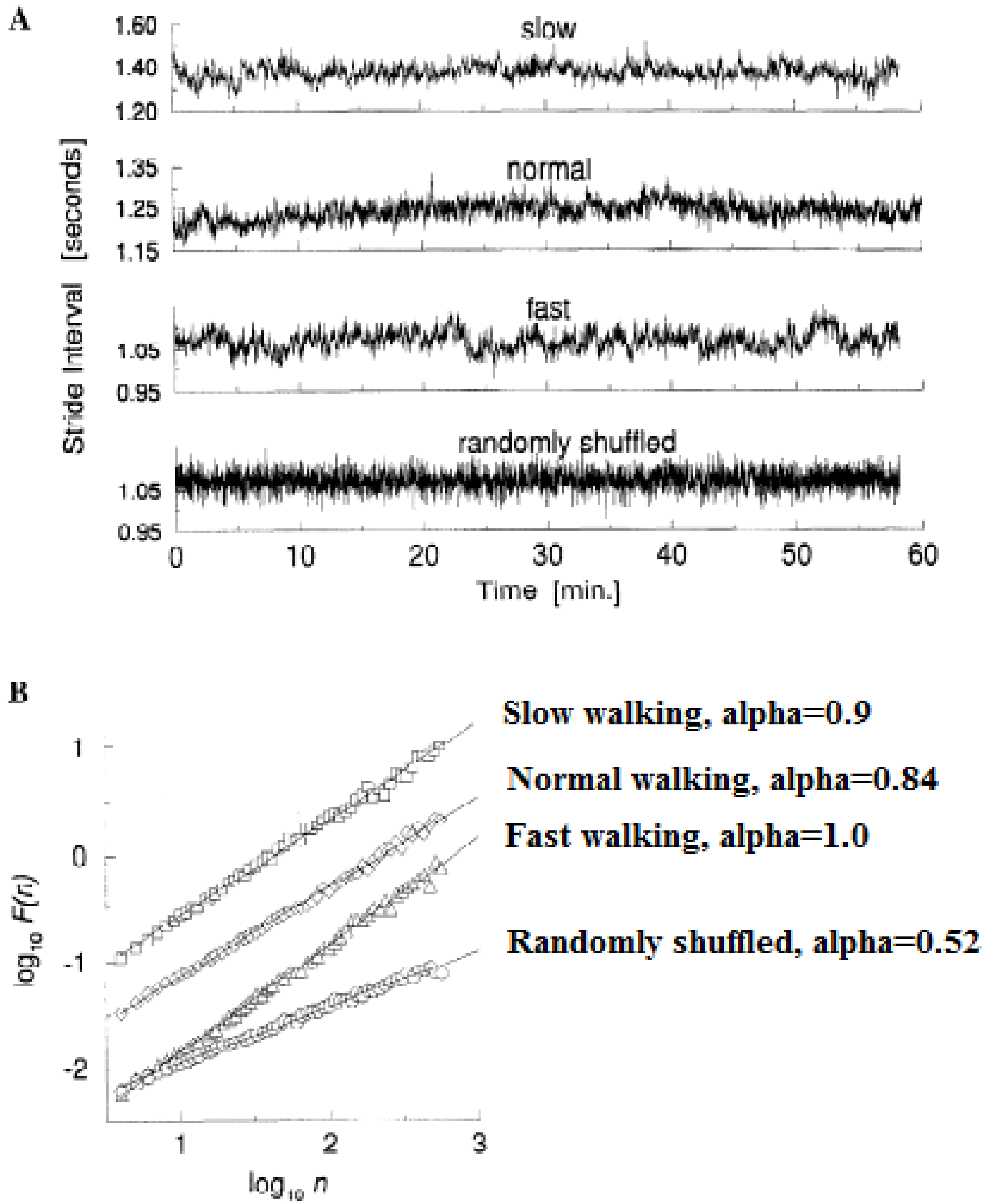
Detrended Fluctuation Analysis (DFA)

$$y(i) = \sum_{t=1}^{i} [x(t) - \bar{x}] \qquad for\ i = 1,2,3, \dots, N$$

- Then, y(i) should be separated into n non-overlapping windows in the same size (s).
- The local trend (y_n) at each interval should be calculated using least square fitting of the data. The fluctuation function can be computed as:

$$F(n) = \sqrt{\frac{1}{N} \sum_{i=1}^{N} [y(i) - y(i)_n]^2}$$

- The slope of the graph of $F(n)$ as a function of n in log-log scale is called the scaling component or self-similarity exponent α.



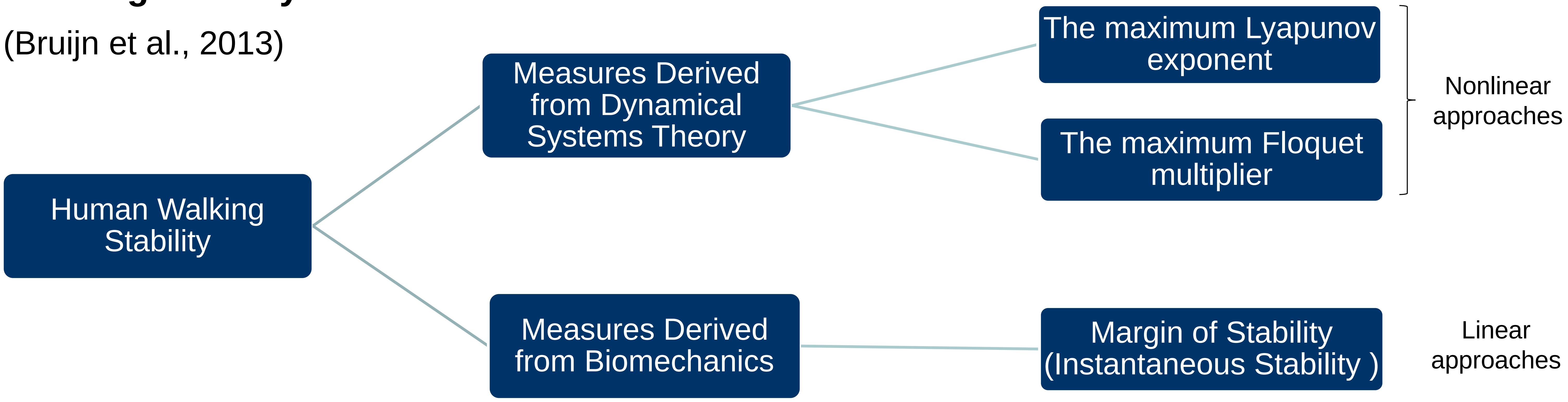
Study 1

- $\alpha = 0.5$ when the time series is random or uncorrelated and behaves like Gaussian (white) noise.
- If $\alpha = 1$, the time series will behave like pink noise, or its power spectral density has an inverse relationship with frequency.
- The time series may be estimated as Brownian noise provided that $\alpha = 1.5$.
- As long as the alteration of α is limited between 0.5 and 1, the time series will have a long range correlation.

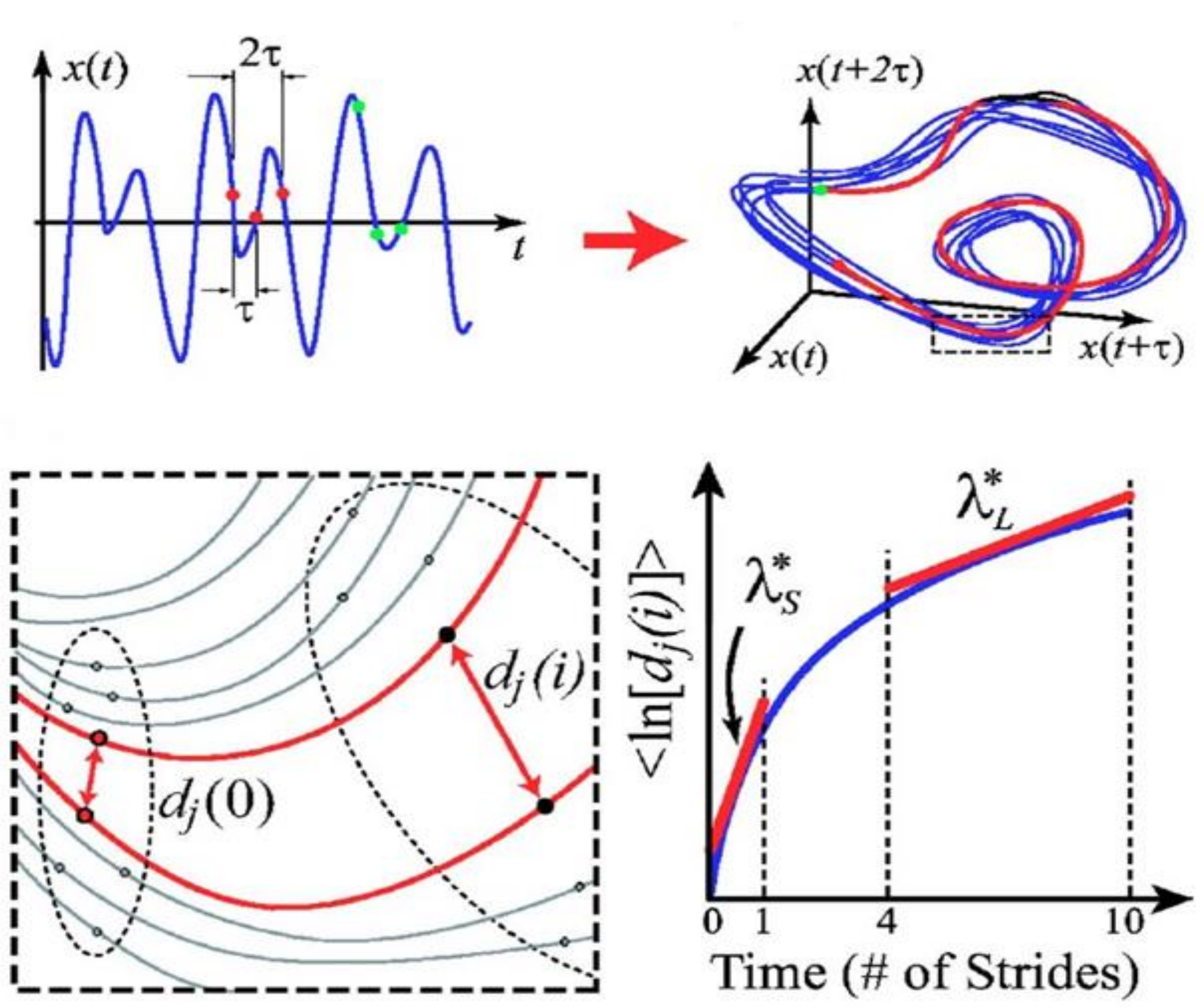
Study 1

- **Methods to Study Walking Stability**

  (Bruijn et al., 2013)



Study 1



- **Techniques derived from nonlinear dynamics theory**
  - *Local Dynamic Stability*

- Local stability refers to the behaviour of a system in response to very small perturbations.

- The maximum Lyapunov exponent (λ) quantifies the average logarithmic rate of divergence of a system after a small perturbation (Rosenstein et al., 1993).

Study 1

- $S(t) = [x(t), x(t+\tau), x(t+2\tau), \dots \dots, x(t+(d_e - 1)\tau]$
- where τ is the time delay and d_e is the embedding dimension
- The time delay for each set of data was estimated using the Average Mutual Information (AMI) function.
- The rate of divergence of nearest neighbouring trajectories was estimated using LyE with

$$D_j(i) = C_j e^{(LyE)*t}$$

- where $D_j(t)$ is the distance between adjacent markers trajectories and C_j is the initial distance between the trajectories.

Study 1

- Taking the Napierian logarithm of both sides and least-square curve fitting to the mean data yields

$$y(i) = \frac{1}{\Delta t}\langle \ln d_j(i) \rangle = LyE.i + c, c = \frac{\ln C_j}{\Delta t}$$

- where LyE is the slope of the fitted line and used as proxy for stability. Higher LyE values indicating more divergence of nearest neighbours and lower stability, and lower LyE values indicating more convergence of adjacent neighbours and higher stability.

Study 1

- Step width, step time, double support time and step length time series exhibited strong statistical persistence during all walking conditions (DFA Exponent >> 0.5).
- DFA Exponent of step time and step length time series did not differ significantly between dual-task trials and baseline walking ($p>0.05$).
- For step width, decreased DFA exponent was observed during texting, reading and talking while walking, but it was not statistically significant ($p>0.05$).

Study 1

- It has been shown that existence of long-range correlation reflects a natural healthy system.

- However, Dingwell and Cusumano (2011) reinterpreted this phenomenon in a recent study and linked persistency of a data set with its level of control during walking. In other words, the more tightly controlled a variable, the less persistency.

- Following this interpretation, the reduced long-range correlation of step width during the talking task compared to other conditions might be explained by its higher variability, suggesting that participants attempted to maintain balance during talking task by regulating and tightly controlling step width.

Study 1

- Texting while walking caused increase in LyE of the head movement in the mediolateral direction compared to that during baseline walking and approached statistical significance ($p=0.052$).

- Reading and talking during walking also resulted in increased head LyE in the mediolateral direction, but was not statistically significant ($p>0.05$).

- There were no significant changes in LyE values of the head motion in the anteroposterior and vertical directions during dual-task trials relative to baseline walking ($p>0.05$)

Study 1

- We found higher sensitivity of local stability in lower extremity joints to perturbations arising from texting during walking compared to those arising from reading and talking while walking in either direction.

compensatory mechanism to maintain stability in the mediolateral direction, which was demonstrated by Kao et al. (2015), and is likely to have contributed to the high variability in step-width observed in the present study [34]. In fact, individuals' effort toward extending of the BoS area are driven by alteration of joint mechanics [85].

Study 1

- These results may be explained by increased variability of the step width during cell phone-based dual-tasking trials, which has been previously reported as well.

- Limited arm swing as a consequence of cell phone usage may results in altered step width as a compensatory mechanism to maintain stability in the mediolateral direction, which was demonstrated by Kao et al. (2015), and is likely to have contributed to the high variability in step-width observed in the present study.

- In fact, individuals’ effort toward extending of the BoS area are driven by alteration of joint mechanics.

compensatory mechanism to maintain stability in the mediolateral direction, which was demonstrated by Kao et al. (2015), and is likely to have contributed to the high variability in step-width observed in the present study [54]. In fact, individuals' effort toward extending of the BoS area are driven by alteration of joint mechanics [85].

Study 1

- In response to perturbations associated with talking on a cell phone during walking, participants adopted a cautious gait pattern characterised by increased step parameters.

Study 2

- ***Biomechanical Differences Between Healthy, Osteoarthritic and Post-Operative Medial Stabilized Knees***

- Total knee replacements (TKRs) are designed to be functional and comfortable. Whilst most TKRs are successful in providing pain relief and basic mobility and stability to patients, they may not be functioning like a normal knee. This unnatural biomechanics has the potential to lead to long-term failure.

Study 2

- In an effort to improve knee biomechanics in TKR patients, some designs have focused on altering the articular surface geometries to encourage medial pivoting, such as the medial stabilizing knee implants. The philosophy is that these designs produce more natural knee motion and, hence loading.

- However, the literature does not adequately substantiate this claim, as there are still mixed reports.

- Therefore, this study aimed to use gait analysis to investigate the knee kinetics of a medially stabilizing knee, comparing it to a healthy control group, as well as to its pre-operative state. It was hypothesized that the TKR knees would experience moments which are more similar to the healthy control group knees.

Study 2

- This observational study recruited two cohorts of participants: a TKR patient cohort (n=8) and an age-matched healthy control cohort (n=11). Eight patients who were assessed as having late-stage knee osteoarthritis (OA) were invited to participate in this gait study.

- All patients were operated on by a single surgeon (JS) and were implanted with a medial stabilizing knee prosthesis (GMK Sphere, Medacta International). These patients participated at two time-points: once 4-6 weeks prior to surgery and again at the 12 months post-surgery time point. The healthy control cohort were only required to attend the gait data collection once.

Study 2

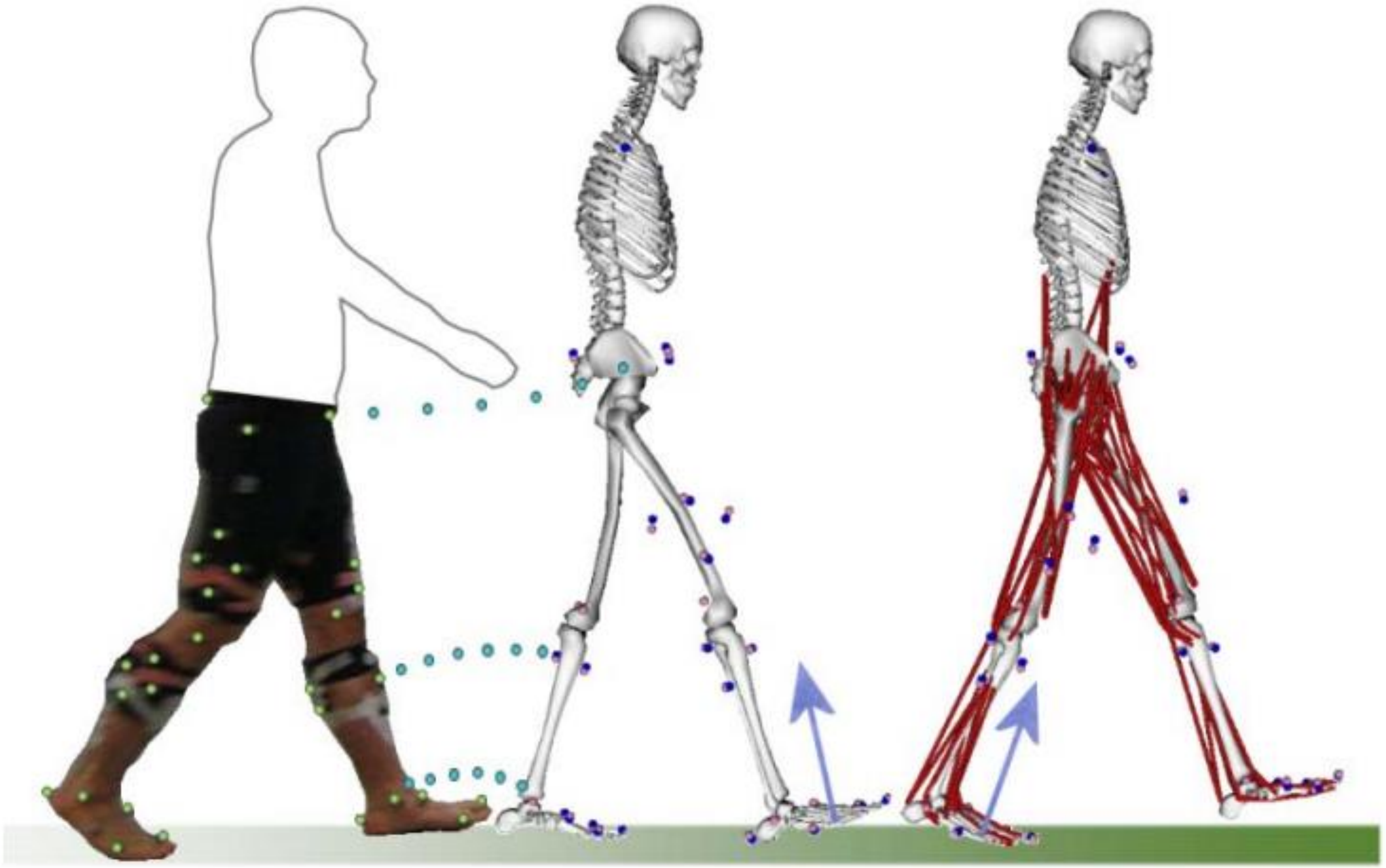
- For all data collection time points, participants were asked to walk at a comfortable, self-selected speed in a gait laboratory.

- Kinematic and kinetic data were collected using an 8 camera Vicon motion capture system (Vicon, Oxford, UK) and three force platforms (Kistler, Winterthur, Switzerland).
- Collected data were filtered using a low pass 4th order Butterworth filter at 6 Hz and 40 Hz, respectively.

- Subject-specific musculoskeletal models were developed in OpenSim for each participant using a modified version of the Gait2392 model.

- The knee joint moments during stance phase were computed for every control, pre-op and post-op trial following inverse kinematics and inverse dynamics, and then averaged for each patient. Mixed model regression analysis was used to compare the peaks in the moment curves.

Study 2



Study 2

Figure 1:Flexion Moments for Osteoarthritic (Pre-operative), TKA (Post-operative) and Healthy Controls

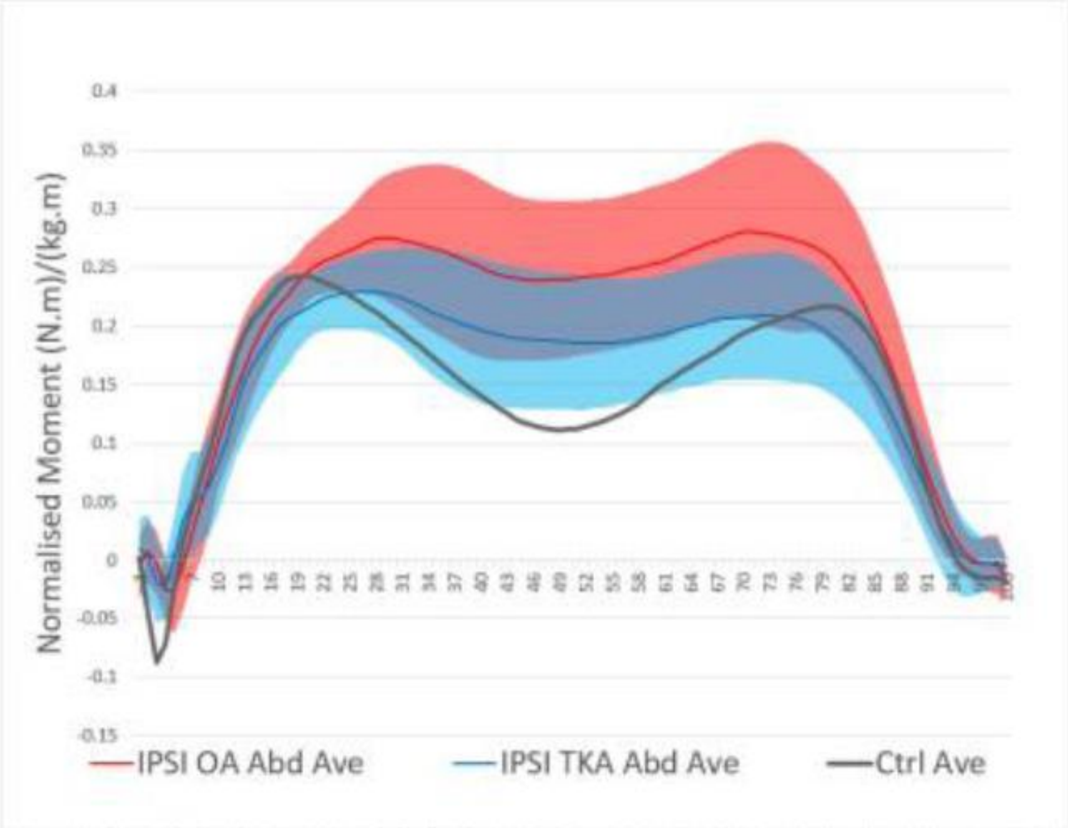


Figure 2: Adduction moments for OA (Pre-operative), TKA (Post-operative) and Healthy Controls

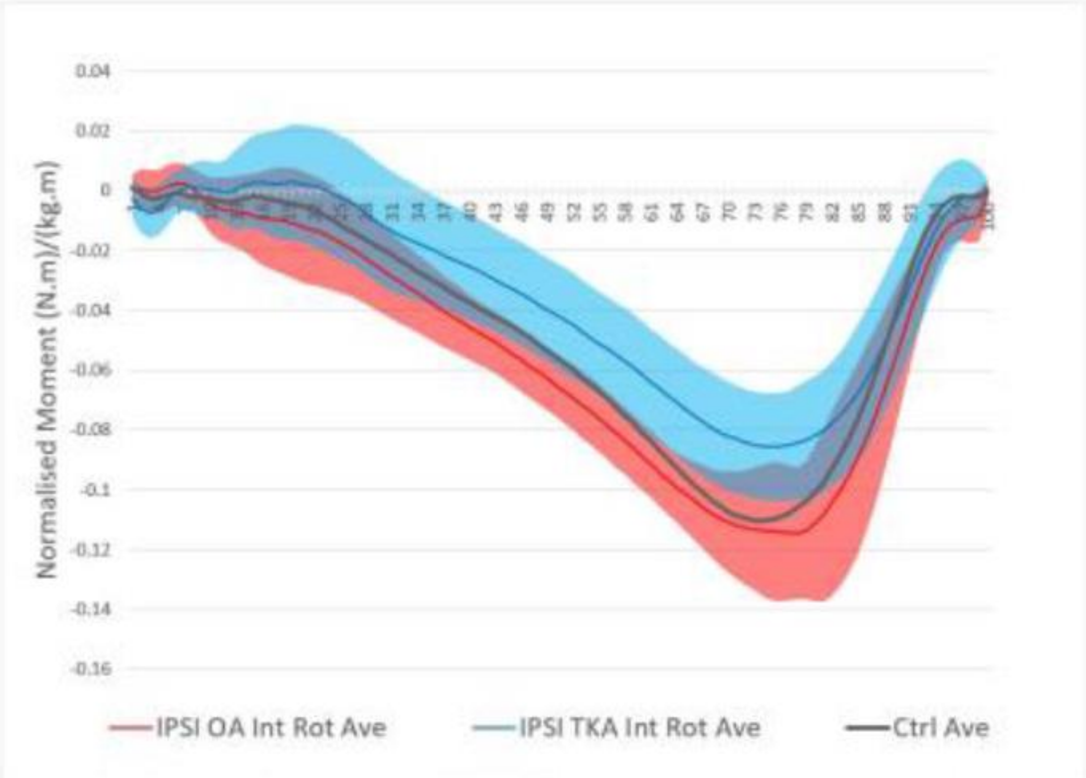


Figure 3: External Rotation Moments for OA (Pre-operative), TKA (Post-operative) and Healthy Controls

Study 2

- This study found the medial stabilizing TKR to produce knee moments closer to that of a healthy knee, compared with an osteoarthritic knee, in both the sagittal and coronal planes.
- The increase in knee flexion moment after surgery suggest an improved ability to load the knee joint, as is evident in confidence shown by patients when they present for their post-operative data collection.
- The knee adduction moment (KAM) of patients post-operatively also better resembled the healthy cohort.
- The medial stabilizing knee in this study exhibited kinetic behaviour similar to that of the healthy age-matched knee, therefore providing confidence in its ability to perform well clinically.

Future Directions

- Development of Neuromusculoskeletal Modelling and Simulation of human movement
- Inclusion of CT and MRI images into modelling process
- Data Collection using more straightforward approaches
- Data analysis using novel methods e.g. machine learning

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Questions

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