KING'S College LONDON

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Design and Control of Articulated-Soft Reconfigurable Lower-Limb Exoskeletons for Stroke Rehabilitation:

The Potential for 6G Technology in terms of enabling Patient-Specific Human-in-the-Loop Rehabilitation in Residential Settings

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I. Background & Challenges
Stroke Figures

- *Stroke* is the second leading cause of death and third leading cause of death and disability globally[1,2] – it currently constitutes a major healthcare challenge.
- A worldwide total of *15 million* people afflicted by *strokes* every year, resulting in 6 million deaths; in the UK, there are 100,000 new casualties per annum.
- *1.3 million* stroke survivors in the UK alone; ~600,000 of them live outside of a 20km radius from a stroke support group.
- Their global, annual treatment costs exceed *£566 Bn*; £1.6 Bn pounds' worth of NHS spending, and an aggregate cost of £25.6 Bn, per annum.
- Stroke *rehabilitation* requires 45-minute sessions, at least 5 times/week.
- The latter is never achieved in the UK, due to a shortage of NHS staff.

1. GBD 2019 Stroke Collaborators, *Lancet Neurol, vol. 20, pp. 795-820, 2021.*
2. V. L. Feigin et al., "World Stroke Organization (WSO): Global Stroke Fact Sheet 2022," *International Journal of Stroke, 17(1), pp. 18-29, 2022.*

II. EPSRC REST Consortium
Academic Partners

"REST: Reconfigurable lower limb Exoskeleton for effective Stroke Treatment in residential settings" **EPSRC Standard Grant** (EP/S019790/1):

- A collaborative research effort aimed at amalgamating the necessary academic and medical expertise of the following partners:

1. Centre for Robotics Research (CoRe), Department of Engineering, Faculty of Natural, Mathematical & Engineering Sciences, King's College London
2. Faculty of Engineering, University of Leeds
3. Faculty of Medicine and Health, University of Leeds

https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S019790/1

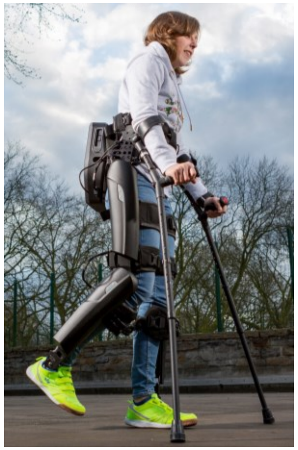
NHS The Leeds Teaching Hospitals NHS Trust

EPSRC Engineering and Physical Sciences Research Council

III. Motivation
Existing Exoskeleton Devices

- An array of various lower-limb exoskeleton designs exists, including the:

1. Soft ankle-foot orthosis device (Park et al.)
2. Treadmill-based gait training robotic orthosis (Huang et al.)
3. Humanoid lower limb exoskeleton (Wan et al.)
4. Knee-ankle-foot orthosis device (Sawicki et al.)
5. Hybrid-drive exoskeleton (Hyon et al.)
6. Compliant robotic ankle orthosis (Adolf)



in addition to other commercially available exoskeletons (e.g. Erigo, Lokomat, LOPES, ReWalk, etc.)

III. Motivation
Lower-Limb Rehabilitation Systems

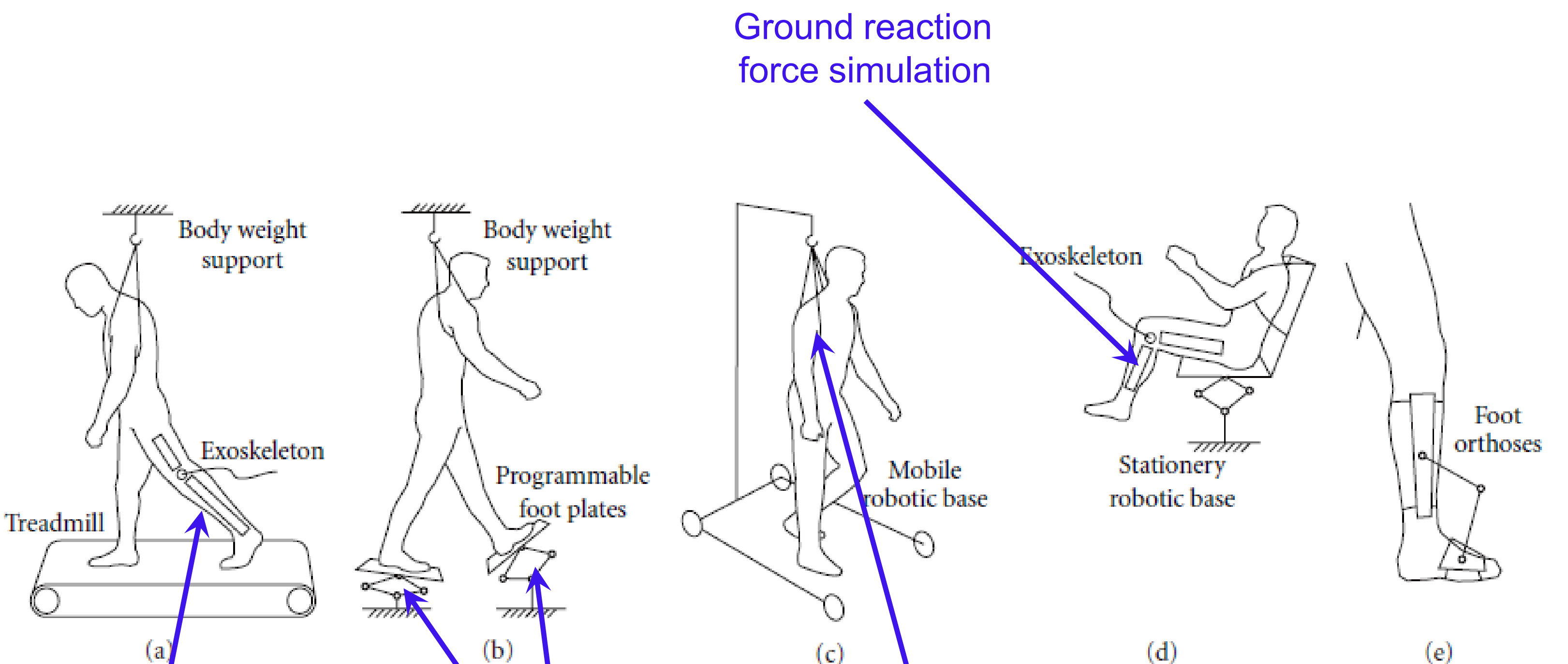


FIGURE 1: Robotic system types for lower-limb rehabilitation: (a) treadmill gait trainers, (b) foot-plate-based gait trainers, (c) overground gait trainers, (d) Stationary gait trainer and (e) ankle rehabilitation systems.

*Díaz, I., Gil, J. J., & Sánchez, E., Journal of Robotics, (2011).

III. Motivation
Lower-Limb Static Rehabilitation Devices

Problem Statement:
- 15m stroke incidents/annum
- 1.3m stroke survivors in the UK
- £1.6 Bn NHS spending; £25.6 Bn per annum aggregate cost

Collaborators:
- University of Leeds
- Leeds Teaching Hospitals

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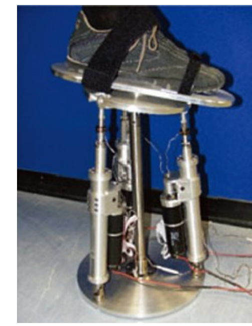
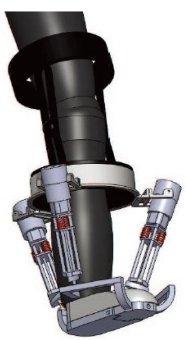
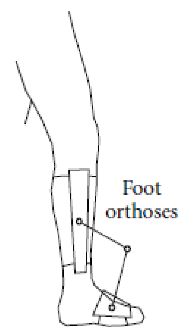


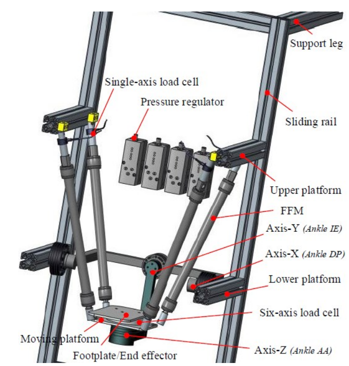
Existing Ankle Rehabilitation Devices

Non-wearable static devices
- parallel with central strut
- compliant static rehabilitation
- 3, 4-DoF reconfigurable

Wearable static devices
- active foot orthosis
- 3 UPS wearable







III. Motivation
Financial Constraints

- The cost of each of these platforms exceeds *£200,000*.
- They are designed for *high-resource* medical settings.
- Over 600,000 patients live within (or exceeding) *20km* distances from local rehabilitation centres.
- Regular attendance of rehabilitation sessions is therefore arduous.
- Hence, there is a need for ‘*domestic*’ rehabilitation, i.e. rehabilitation routines conducted in *residential* settings.

IV. State-of-the-Art Devices
Residential Rehabilitation

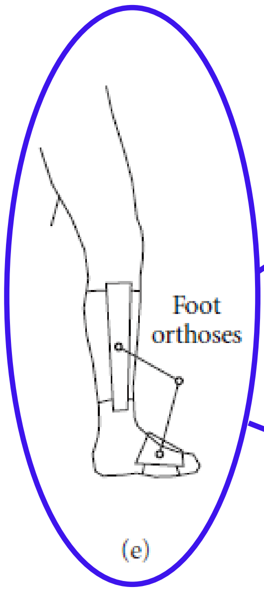
- There exists a limited number of residential rehabilitation prototypes:

1. Soft robotic glove for finger rehabilitation (Harvard)
2. Long-distance collaborative rehabilitation (Johnson)
3. ASIBOT assistive robot (Huete et al.)
4. EKSO – robotic exoskeleton available in the UK market

- Three impediments to wide/r adoption of these devices:

1. Lack of *reconfigurability* and customisability
2. Insufficient levels of robotic *intelligence* for automated recovery progress evaluation
3. Lack of effective *personalised treatment* methods

IV. State-of-the-Art Devices
Ankle Rehabilitation Systems

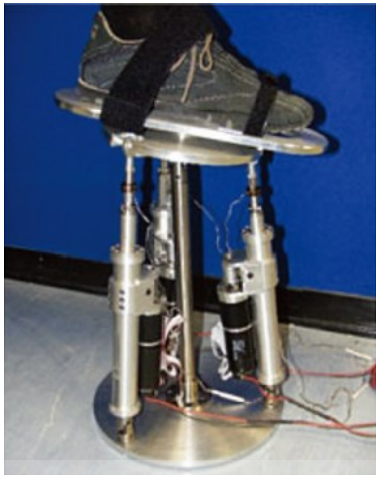


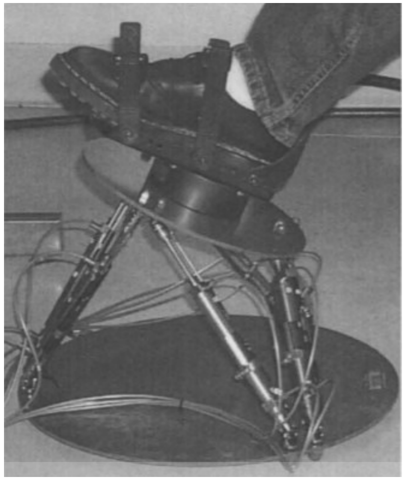
(e) ankle rehabilitation systems.

Active foot orthoses

Actuated exoskeletons, used to control ankle position and overall motion, compensate for weaknesses and correct deformities.

Static Rehabilitation Systems



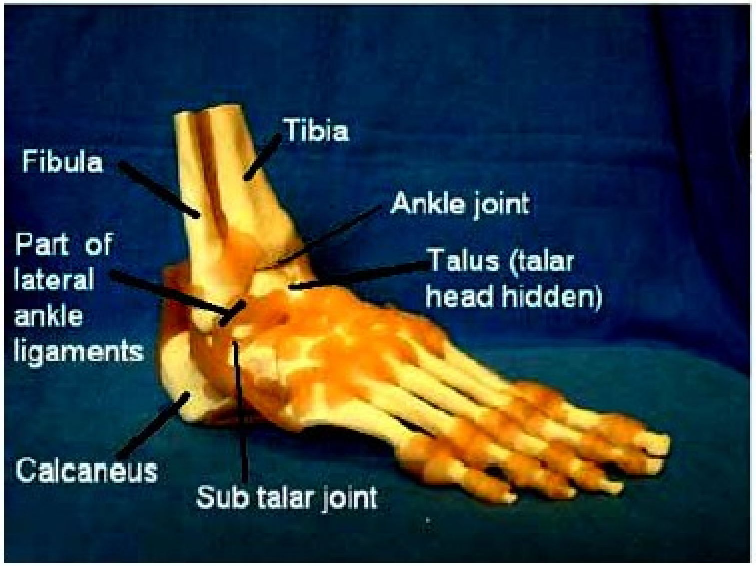


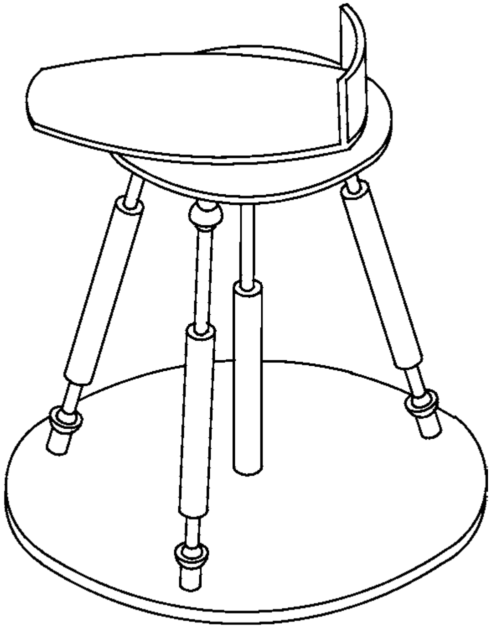
*Girone, M., et al., Autonomous robots, (2001).

*Saglia, J. A., et al., The International Journal of Robotics Research, (2009).

IV. State-of-the-Art Devices
Static Rehabilitation Devices

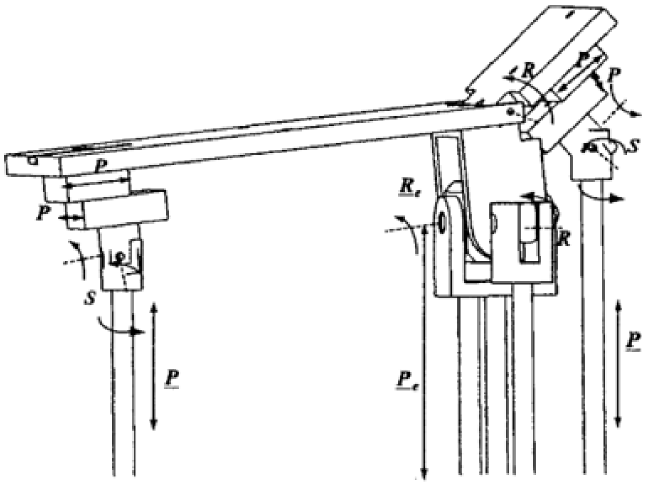
❖ Parallel Mechanism with a Central Strut
  - An upper ankle joint that supports the rotational dorsiflexion/plantarflexion motion

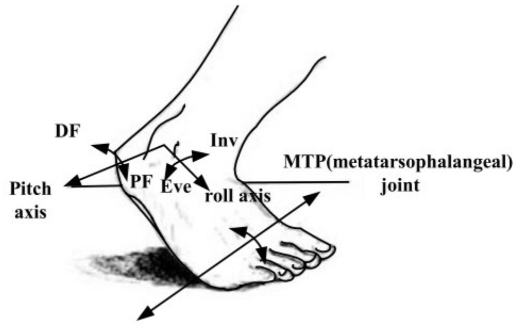


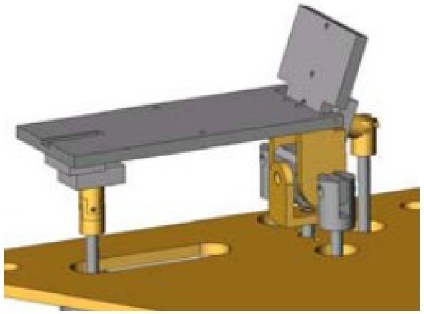


*Dai, J. S., Zhao, T., & Nester, C., Autonomous Robots, (2004).

IV. State-of-the-Art Devices
Static Rehabilitation Devices







MTP motion

DP, IE & MTP motion exercise

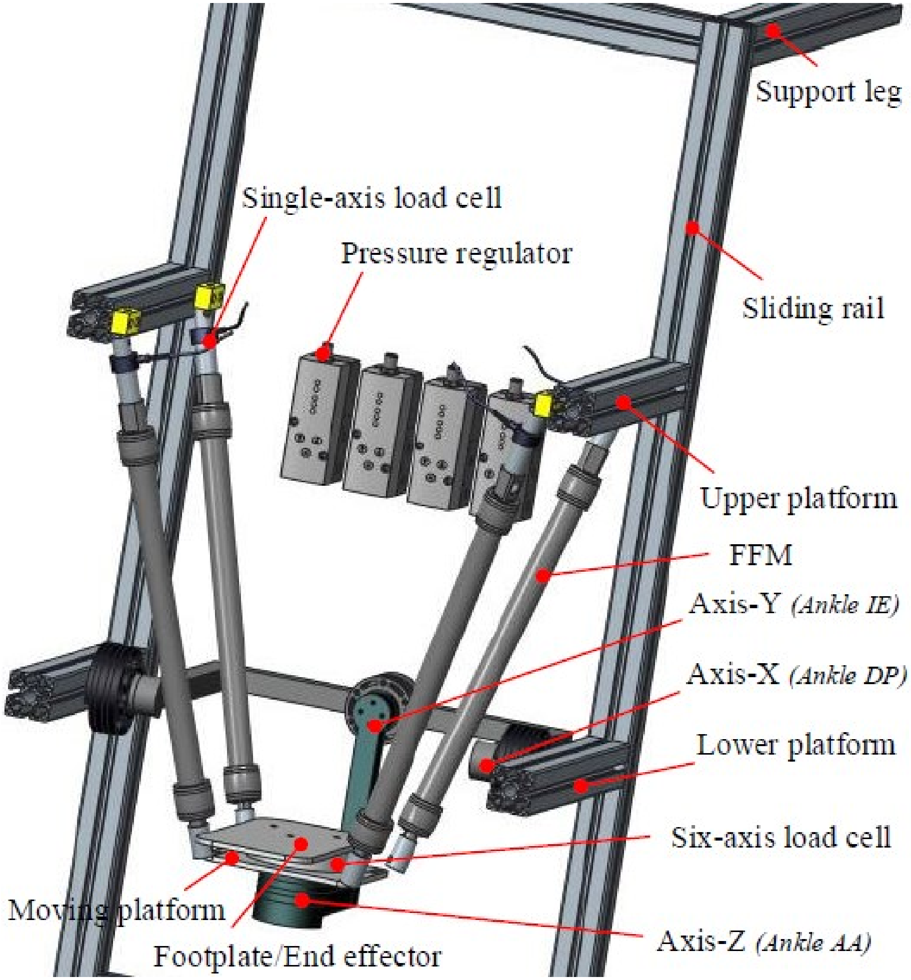
(a) ROM/strengthening type

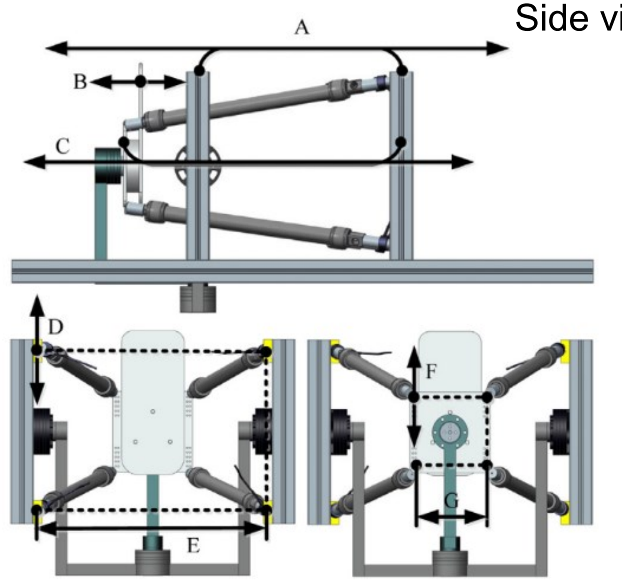
For heave motion exercise

(b) balance/proprioception type

*Yoon, J., & Ryu, J., IEEE International Conference on Robotics and Automation (2005).

IV. State-of-the-Art Devices
Compliant Static Rehabilitation Devices





4 SPS (S: sphere joint, P: prismatic joint)
3 rotational degree of freedoms (DOFs)
4 compliant actuators
(Festo fluidic muscles)

Drawback: Maximum plantarflexion is less than the actual biological ankle motion

*Zhang, M., Doctoral dissertation, (2016)
*Zhang, M., et al., Robotics and Autonomous Systems (2017).

IV. State-of-the-Art Devices
Wearable Static Rehabilitation Devices

Design of a Reconfigurable Force Feedback Ankle Exoskeleton for Physical Therapy

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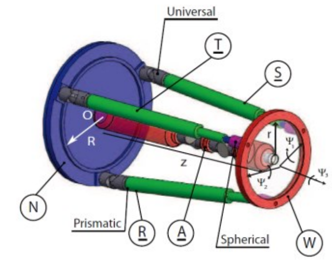
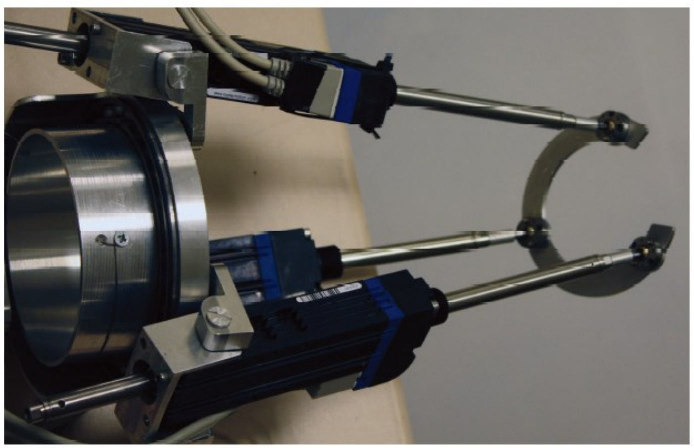
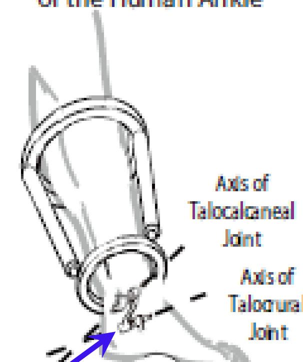


3UPS

Kinematic Model of the Human Ankle



Early prototype of Sukorpion AR robot



Spatial serial kinematic chain with two revolute joints

V. Objectives & Workplan
Project Aims

- Development of a *reconfigurable* exoskeleton:
  - Capable of being structurally/mechanically adjusted to befit the patients' needs.
  - Modular and adaptive compliance mechanism and software required.

- Automatic disability *assessment*:
  - Quantitative evaluation of patients' disabilities.
  - Requires understanding of human lower limb mechanics and development of real-time exoskeleton lower-limb models.
  - Correlation between sensor measurements and movement performance.

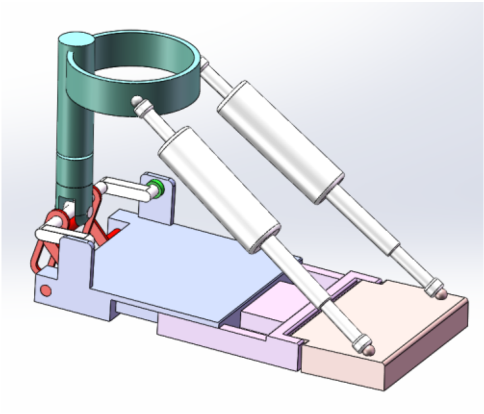
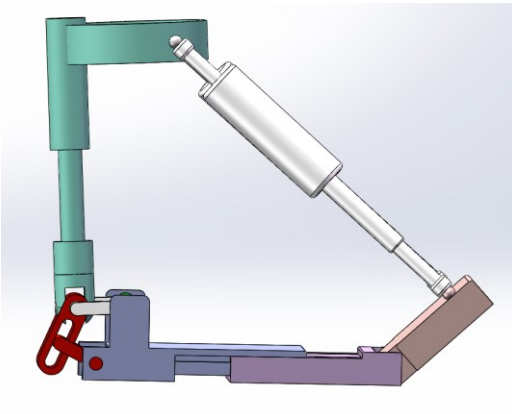
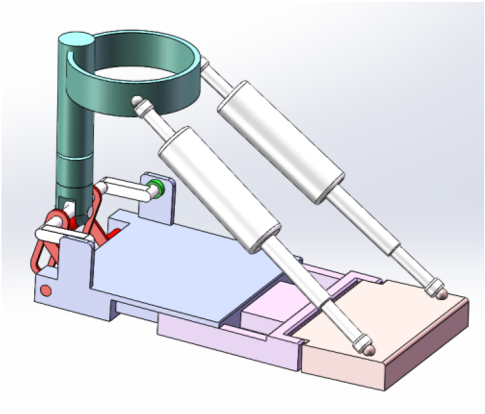
- *Evidence-based* treatment strategies:
  - Conversion of currently-employed 'open loop' rehabilitation to 'closed-loop' rehabilitation, e.g. human-in-the-loop control or data acquisition.
  - Generation of optimal patient-specific treatments.

Potential for significant improvement via 6G technology

V. Objectives & Workplan
Initial Preliminary Design

- A simple, preliminary design to understand the prospective actuator topology, torque requirements, and link-length adjustability.

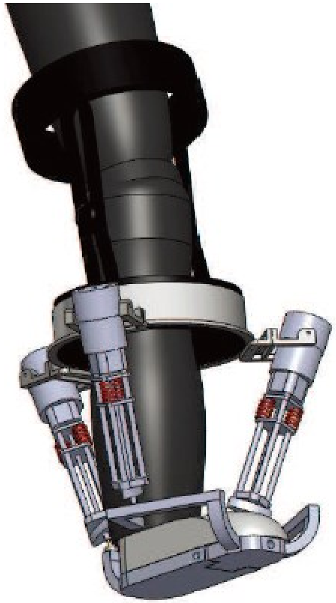
- Generation of a conceptual design permitting ankle motions along the pitch, roll, and yaw axes.

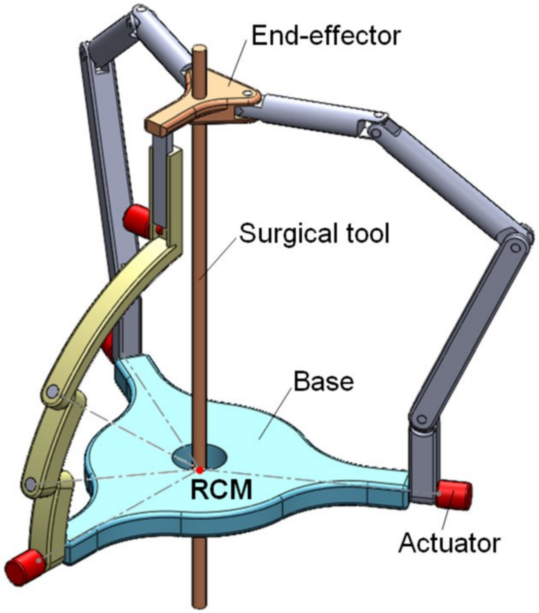
V. Objectives & Workplan
Reconfigurability-Augmented Design

- Introduction of *reconfigurability* for improved flexibility, versatility, and repeatability of motions, in a scientifically sound manner.

- Leveraging of the *Remote-Centre-of-Motion* concept, to enable efficient and intuitive actuation of the patient's ankle pitch joint.



SUkorpion AR in 3RPS Configuration



4-DoF Parallel Manipulator

V. Objectives & Workplan
Hardware Selection

- The mechanical *designs* were guided by kinematic analyses to ensure that the patient kinematic workspace constraints were satisfied.

- Dimensional and performance-related *actuator* requirements were procured, by means of dynamical simulations.

- Simulation models accounted for the full system dynamics.

- The entire workspace was explored to ensure that the actuators can accurately and robustly compensate for the *dynamical effects*.

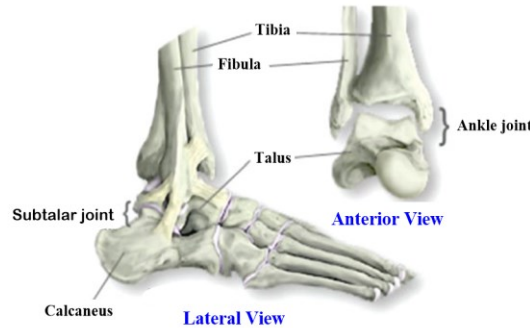
- The *motor parameters* were automatically generated via the simulation.

VI. REST Project Outcomes
Reconfigurable Robotic Exoskeleton

Design Requirements:

Lower-limb, reconfigurable exoskeleton:

- ‘domestic’ rehabilitation
- dynamic/static rehabilitation
- anatomical adaptability
- automatic disability assessment
- evidence-based treatment



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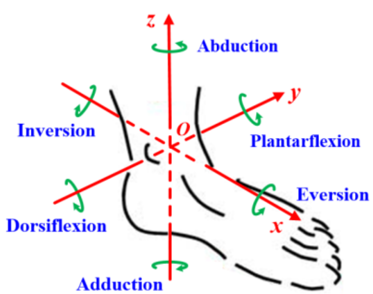
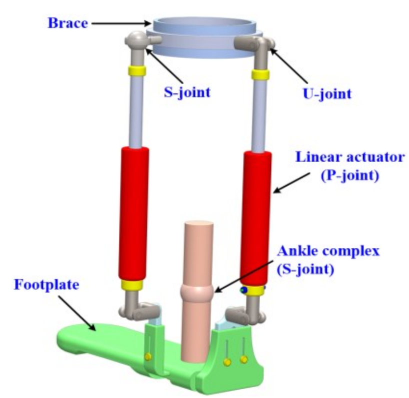
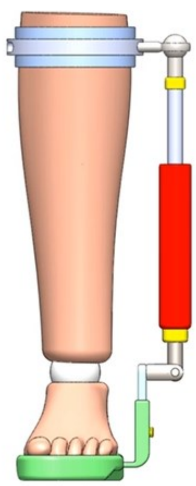
Main Features of Proposed Design:

- human leg = central strut
- rotational centre - ankle alignment
- patient workspace ⊆ reachable region
- lightweight & portable
- singularity-free operation
- decoupled control
- 3-DoF extensibility







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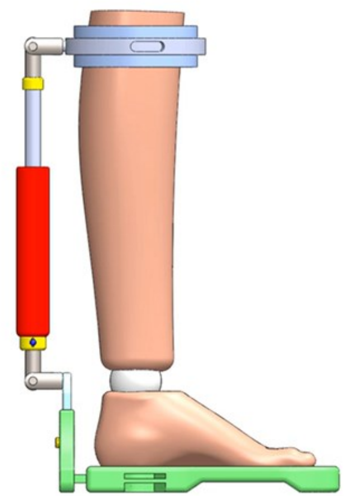
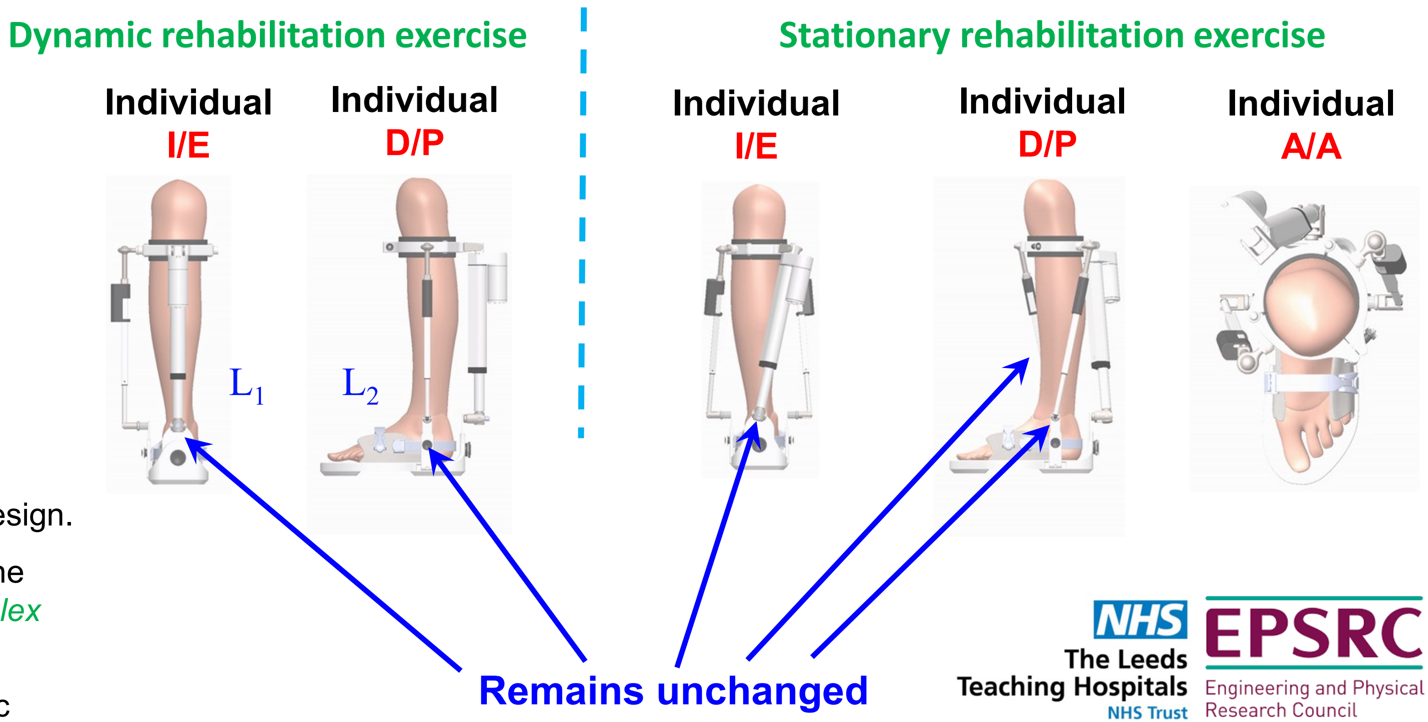


Dorsi-/Plantarflexion

VI. REST Project Outcomes
Reconfigurable Lower-Limb Exoskeleton

"REST: Reconfigurable lower limb Exoskeleton for effective Stroke Treatment in residential settings" **EPSRC Standard Grant** (EP/S019790/1) (https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/S019790/1):

- Bringing robotic *rehabilitation* to people's *homes*.
- Exoskeleton designs adaptable to a wide range of distinct human *anatomies*, i.e. suitable for a wide range of patients.
- *Static & dynamic* rehabilitation using a single mechanical design.
- Perfectly matching the human's *ankle complex* – increased comfort.
- Potential for dramatic reduction of NHS *spending*



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- T. Wang, Y. Lin, **E. Spyrakos**, S. Xie, J. Dai, "Stiffness evaluation of a novel ankle rehabilitation exoskeleton with a type-variable constraint," *Mechanism and Machine Theory, vol. 179, 2023.*
- T. Wang, **E. Spyrakos**, J. S. Dai, "Design and Analysis of a Novel Reconfigurable Ankle Rehabilitation Exoskeleton Capable of Matching the Mobile Biological Joint Centre in Real-Time," *Transactions of the ASME Journal of Mechanisms and Robotics, vol. 15, no. 1, 2023.*
- T. Wang, E. Olivoni, **E. Spyrakos**, R. J. O'Connor, J. S. Dai, "Novel Design of a Rotation Center Auto-Matched Ankle Rehabilitation Exoskeleton With Decoupled Control Capacity," *ASME Journal of Mechanical Design, vol. 144, no. 5, 2022.*

VII. Evidence-based Treatment Strategies
Remote Biosignal Processing via 6G Networks

- Rehabilitation programmes should ideally be tailored to *patients' needs*.
- This requires the recording of *biosignals*, e.g. ECG, EMG, and EEG.
- These *biosignals* are then fed to an AI/ML-based control algorithm that adapts the rehabilitation routine's *trajectories to generate* an optimal, patient-specific treatment.
- Broadcasting these signals to a central PC located in a clinic/rehabilitation centre can be a *bandwidth-intensive* process.
- *6G technology* could therefore offer a solution to this problem and help convert 'open loop' rehabilitation to 'human-in-the-loop' rehabilitation.
- Does *trajectory generation* alone suffice to ensure *safe* rehabilitation?

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VIII: The Quest for Soft(er) Exoskeletons:

Limitations of Rigid-Joint Robots

- Traditionally, robotics has been *confined* to industrial settings and research labs.

- Industrial manipulators comprise *rigid* joints aimed at high *repeatability;* however, these systems are only capable of executing a *limited range* of *tasks*.

- Although these devices are capable of achieving high *positioning* accuracy, their *rigid* joints could be detrimental to *interactional* safety.

- *Force* sensing can be incorporated into such manipulators; however, the absence of passive *compliance* still implies *slower* response times.

- Hence, due to their potentially limited *safety*, this precludes the usage of *rigid-joint* robots in residential settings, in close proximity to humans.

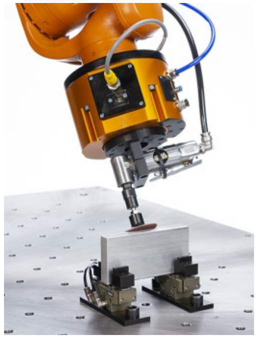
VIII: The Quest for Soft(er) Exoskeletons:

Compliant Interaction: A Key Enabler of Safe Rehabilitation

- For as long as robots are deemed *unsafe*, their introduction into human-inhabited environments will inevitably be delayed. So, how can we render robots *safe*?
- There are two distinct means of achieving this:
  - Passive *Interaction* Control via *Hardware* Development
  - Active *Interaction* Control via *Algorithmic* Development
- *Hardware* development typically entails incorporation of advanced sensing equipment, or incorporation of physical *compliance*, i.e. *springs* or *flexible* joints.
- *Algorithmic* development focuses on the creation of sophisticated *interaction* control *algorithms* that can render a robot aware of, and amenable to, its environment.
- Ideally, *hardware*, and *algorithmic*, development should be closely intertwined to maximise *safety*, i.e. *soft* robotic devices controlled using the appropriate algorithms account directly for their *elasticity*.
- *Intelligent soft* robots can theoretically offer a solution to safety in *pHRI*.

VIII: The Quest for Soft(er) Exoskeletons:
Interaction & Force Control

- *Interaction* control is crucial for the execution of practical tasks including:
  - *Machining*
  - *Assembly*
  - *Polishing*
  - *Deburring*
  - *Milling*



- The environment imposes *constraints* on the end-effector's motion (geometric paths) during contact; these are commonly known as *kinematic constraints*.

- Contact with a *stiff* surface is therefore termed "*constrained motion*".

- What would happen if we decided to carry out a *task* involving *interaction* between the *robot* and *environment*, using a simple *motion* controller (e.g. *position* control)?

- This would require accurate pre-planning of the *task*, which would necessitate:
  – An accurate *model* of the *robot* (kinematics/dynamics)
  – A precise *model* of the *environment**.

* How accurately can we model the environment?

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VIII: The Quest for Soft(er) Exoskeletons:
“Stiff” Robot Interaction Video

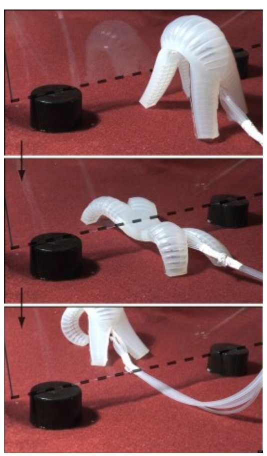
VIII: The Quest for Soft(er) Exoskeletons:
Passive Interaction Control

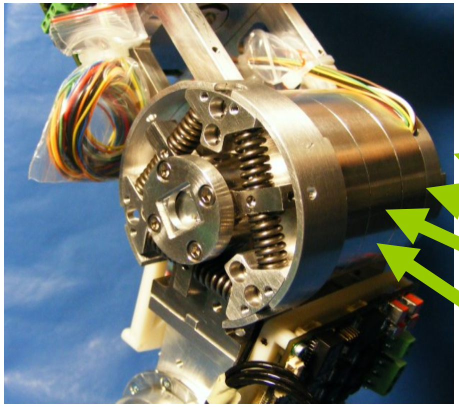
- How does *passive interaction control* work? In *passive interaction* control, the robot end-effector's *trajectory* is modulated by the *interaction*/contact forces, as a result of the *structural deformations* occurring due to the robot's *passive compliance*.

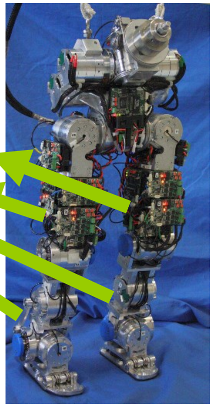
- Hence, *passive interaction control* is achieved by incorporating structural *compliance* into a robot's links, joints, or end-effector through "*flexible*" elements – such devices are referred to as *Articulated-Soft Robots* (*ASRs*).

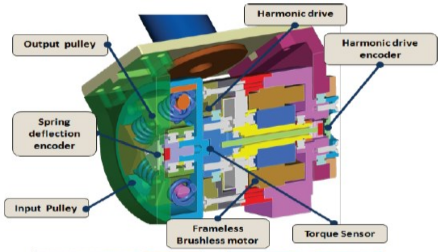
- *Soft* robot arms with *elastic* joints or links (ASRs) are purposely designed for *intrinsically* safe *interaction* with humans and the environment.

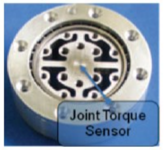
Note: *Passive interaction control* can also be achieved via the *compliance* of the actuator itself, i.e. the combination of transmission elements and gears yields a "flexible" structure.











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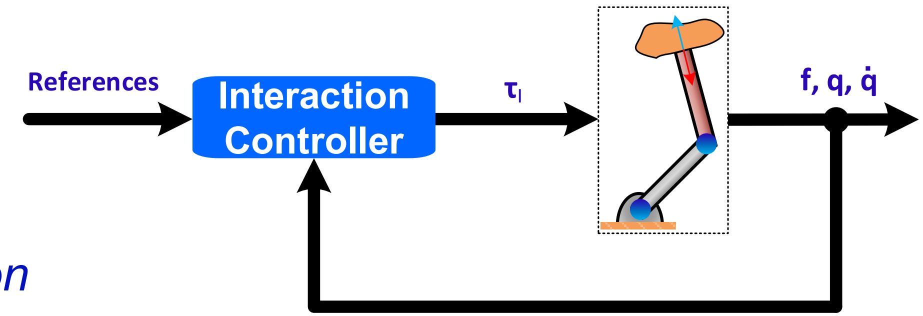
VIII: The Quest for Soft(er) Exoskeletons:
Soft Robot Video

VIII: The Quest for Soft(er) Exoskeletons:
Active Interaction Control

- In *active interaction* control, the closed-loop robotic system is endowed with a degree of *compliance*, through usage of a purposely designed *control system*.

- Some *active interaction* control schemes function by measuring the *contact forces/moments*, and using these to adapt the *end-effector's* trajectory in real time.

- *Active interaction* control can overcome some of the *drawbacks* of *passive interaction* control.



- However, compared to *passive interaction* control, *active interaction* control is:
  - *slower* – as compared to the *physical* response
  - *more expensive: requires advanced electronics and high communication rates*
  - *more complex: necessitates the use of sophisticated, nested controllers*

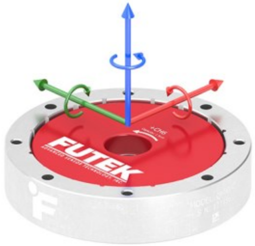
- For efficient operation, *active interaction control* ought to be used in conjunction with a certain degree of *passive compliance**.

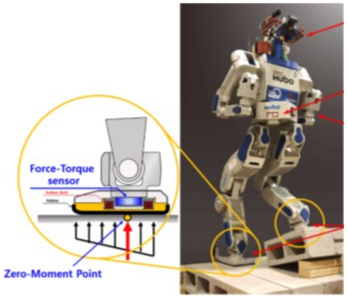
*__Note:__ To "absorb" impacts, one must use passive compliance, which inevitably responds faster than a control algorithm.

VIII: The Quest for Soft(er) Exoskeletons:
Active Interaction Control

- To completely *define* a *force-controlled task*, one must consider *six force/moment* components: *three* translational *force* elements and *three moments/torques*.

- *Force/torque sensors* are typically mounted at a robotic manipulator's *wrist/s*, although they are occasionally attached to the *fingertips* of robotic hands.





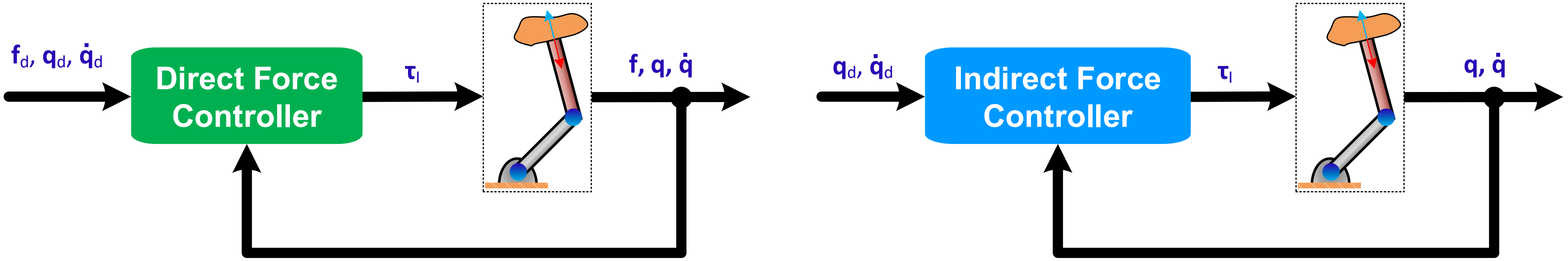
- In *legged* robots, *force/torque sensors* are usually mounted at the foot soles.

- *Force signals* can be acquired in either of the following two ways:
  - *strain* (*gauge*) measurements involving the use of "*stiff*" *sensors*
  - *deformation* measurements involving utilisation of *compliant sensors* (when employing, for example, *optical sensors*)

Note: Sensors relying on deformation measurements introduce compliance, which can be desirable in some applications, although it also induces an additional layer of uncertainty, as the stiffness properties of such a device can be highly nonlinear.

VIII: The Quest for Soft(er) Exoskeletons:
Direct vs. Indirect Force Control

- How do these two *force control* approaches differ from each other?
- *Indirect force control* methods realise *force control* through *motion control,* thus obviating the need for *force feedback,* i.e. they realise *force control indirectly.*
- *Direct force control* methods enable the system/user to control contact *forces/torques* to *desired* values, by incorporating *force feedback* loops.



- The category of *indirect force control* includes *impedance control*, *admittance control*, *stiffness control*, and *compliance control* (among other *permutations*).
- A widely adopted *direct force control* method is *hybrid motion/force* control.

VIII: The Quest for Soft(er) Exoskeletons:
Impedance Control

- Precise *motion* controller: high *impedance* (low *admittance*) to produce small *motion* deviations when subjected to *forces*.

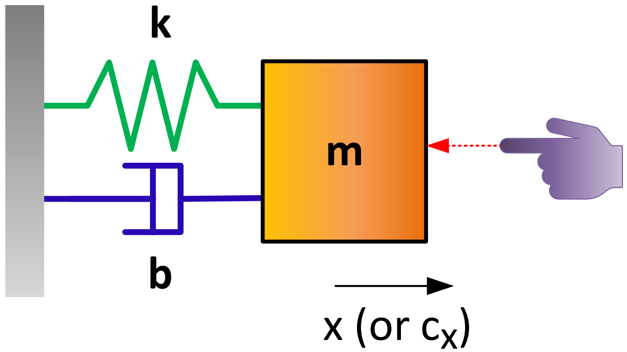
- Robust *force* controller ought to possess low *impedance* (high *admittance*) to produce small *force* deviations in the presence of *motion* errors.

$$\Delta F(s) = Z(s)\Delta X(s) \qquad \Delta X(s) = Y(s)\Delta F(s)$$

- Therefore, *impedance* control aims to realise *task-space* behaviours of the form:

$$\mathbf{M}_C\ddot{\boldsymbol{c}} + \mathbf{D}_C\dot{\boldsymbol{c}} + \mathbf{K}_C\boldsymbol{c} = \boldsymbol{f}_{ext}$$

$\mathbf{M}_C \in \mathbb{R}^{m\times m}$ - virtual mass, $\mathbf{D}_C \in \mathbb{R}^{m\times m}$ - virtual damper
$\mathbf{K}_C \in \mathbb{R}^{m\times m}$ - virtual spring, $\boldsymbol{f}_{ext}$ - external force

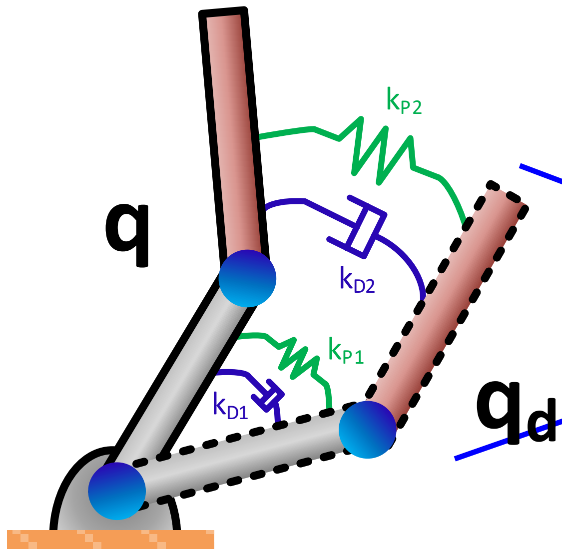


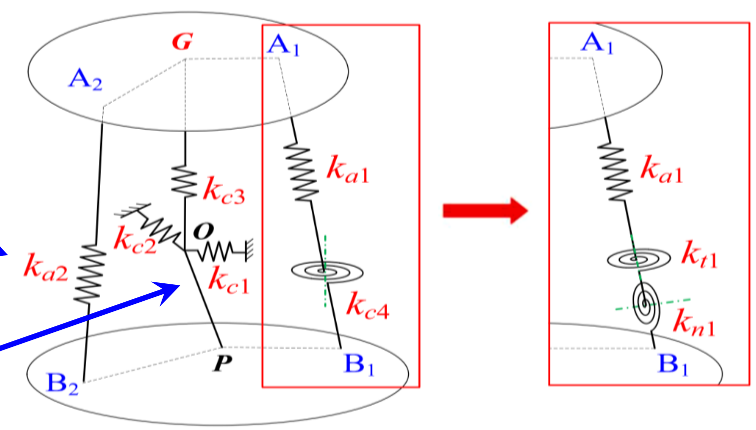
- The objective is, therefore, to shape the robot's dynamics in such a manner that its end-effector will exhibit a desired *mass*–*spring*–*damper* behaviour in the *task space.*

*T. R. Kurfess, Robotics and Automation Handbook, CRC Press, 2005.

VIII: The Quest for Soft(er) Exoskeletons:
Online-Adapted Impedance Control via 6G

- *6G technology* could enable (hard) *real-time* acquisition of patient *biosignals*.
- During a specific rehabilitation routine, these *biosignals* may be sent back to the main PC executing the ML algorithms via a *6G network*, at the desired *bandwidths.*
- These ML algorithms can then be used to generate not only adapted *trajectories* for the exoskeleton, but also *impedance* profiles to ensure patient *safety*.



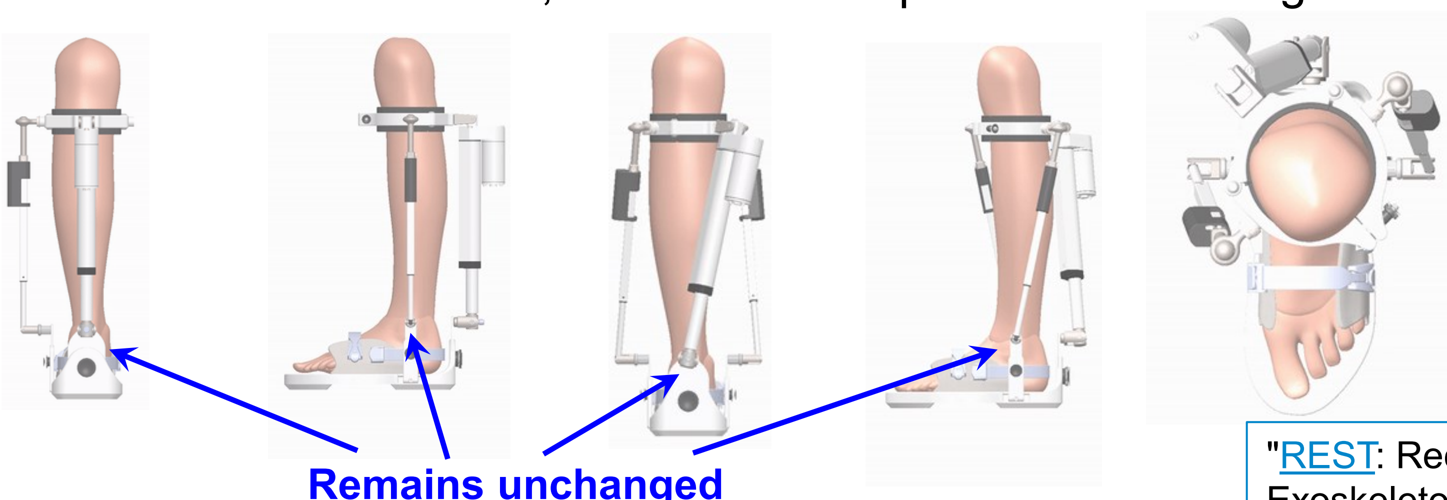


"REST: Reconfigurable lower limb Exoskeleton for effective Stroke Treatment in residential settings"

*T. Wang, Y. -H. Lin, E. Spyrakos, S. Q. Xie, J. S. Dai, Mech. Mach. Theory (**MMT**), 179, 105071, 2023.

VIII: The Quest for Soft(er) Exoskeletons:
Real-Time Reconfigurable Articulated-Soft Robots

- *ASRs* can be adroitly controlled for execution of *pHRI* tasks and *impact* mitigation.
- Can *ASRs* alone address the problem of task *versatility*?
- The development of *reconfigurable* robots can address this problem.
- *Reconfigurability* can engender highly *protean* devices, such as lower-limb exoskeletons, that can be adapted to a wide range of anatomies.



"REST: Reconfigurable lower limb Exoskeleton for effective Stroke Treatment in residential settings"

EPSRC Engineering and Physical Sciences Research Council
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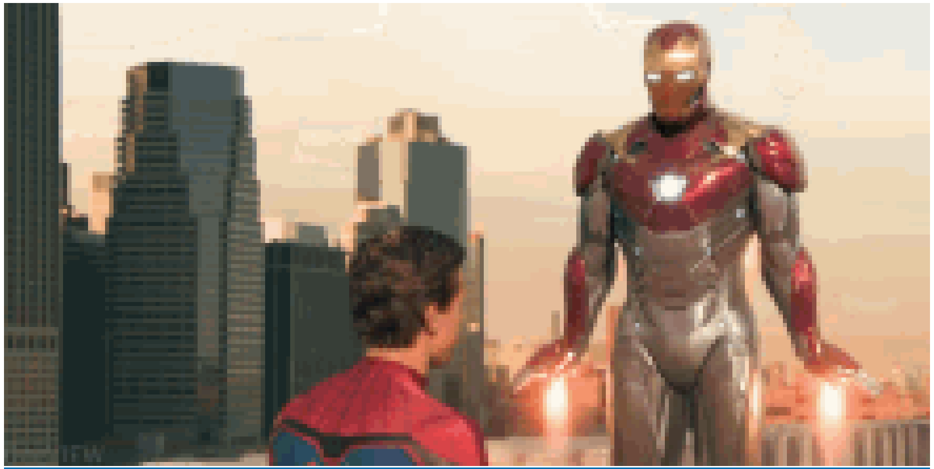
•T. Wang, E. Spyrakos-Papastavridis, J. Dai, ASME Journal of Mechanisms and Robotics, vol. 15, no. 1, 2023.
•T. Wang, E. Olivoni, E. Spyrakos-Papastavridis, R. J. O'Connor, J. S. Dai, ASME Journal of Mechanical Design, vol. 144, no. 5, 2022.

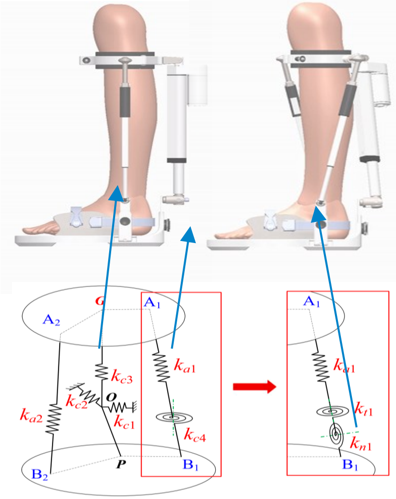
IX. Related Future Work

Real-Time Reconfigurable Floating-base ASRs

- Is it possible to combine task *versatility* with *mobility* using a single design?
- *Reconfigurable floating-base robots* combine both; however, *reconfiguration* induces *downtime/human intervention: an undesirable process of stopping and reconfiguring*.
- *Real-time reconfigurable floating-base robots* can overcome these drawbacks.
- **<u>Aim:</u>** *Real-time reconfigurable floating-base ASRs - <u>versatile</u>, <u>mobile</u>,* and *<u>safe</u>.*



An archetypal form of self-reconfigurability



Articulated-Soft Lower-Limb Exoskeletons

X. Related (Existing) Work
Metamorphic Floating-base Walkers

- We have developed an award-winning, *metamorphic* (self-reconfigurable) quadrupedal robot, namely the *Origaker;* it is capable of switching between disparate forms and *modes* of locomotion, e.g. mammalian, reptilian, entomoid, etc.

2022 ASME Journal of Mechanisms and Robotics "Best Paper Award"

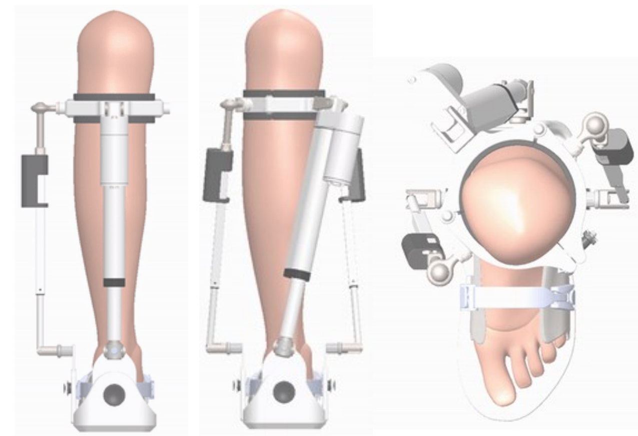
Robotics Influencer

NMES Comms Team

* Z. Tang, K. Wang, E. Spyrakos-Papastavridis, J. S. Dai, "Origaker: A Novel Multi-Mimicry Quadruped Robot Based on A Metamorphic Mechanism," *Transactions of the ASME Journal of Mechanisms and Robotics, vol. 14, no. 6, 2022 ("**2022 JMR Best Paper Award**").*

KING'S College LONDON

Acknowledgment



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Thank you for your attention!