OPTICA
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Technical Groups

Optical Fiber Sensors for the Next Generation of Rehabilitation Robotics

Featuring Anselmo Frizera-Neto, Universidade Federal do Espírito Santo

15 March 2022

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About Our Technical Group

Our technical group focuses on the development and application of optical technologies for the targeted detection of trace biological compounds for molecularly oriented medical diagnostics as well as for alerting to biological threat and contamination.

Our mission is to connect the 2600+ members of our community through technical events, webinars, networking events, and social media.

Our past activities have included:

- Networking event at the Optical Sensors and Sensing Congress
- Webinar on Surface Plasmon Resonance Sensors: Science and Technology

Connect with our Technical Group

Join our online community to stay up to date on our group's activities. You also can share your ideas for technical group events or let us know if you're interested in presenting your research.

Ways to connect with us:

- Our website at www.optica.org/BB
- On LinkedIn at www.linkedin.com/groups/8260947/
- On Facebook at https://www.facebook.com/groups/opticalbiosensorstg
- Email us at TGactivities@optica.org / santosh@lcu.edu.cn

Today's Speaker

Anselmo Frizera-Neto

Federal University of Espirito Santo (UFES)

Anselmo Frizera-Neto holds a bachelor's degree in Electrical Engineering (2006) from the Federal University of Espirito Santo (UFES, Brazil) and a PhD in Electronics (2010) from the University of Alcalá (UAH, Spain). Since 2010, he's held a permanent position as a lecturer and researcher of the Electrical Engineering Department (UFES). From 2014 to 2018, he served as a Member of the Board of AITADIS, contributing to support the dissemination of knowledge in assistive technologies in Iberoamerica. Prof. Frizera-Neto was selected as IEEE Impact Creator (2020), IEEE/EMBS Distinguished Lecturer (2021) and acts as a mentor on IEEE/EMBS Student Mentoring Program (2021). Prof. Frizera-Neto has published more than 300 scientific articles, of which more than 150 are publications in international scientific journals. His research interests are rehabilitation robotics, optical and electronic sensors for human-machine interfaces, biomedical signal processing and smart textiles.

Optical fiber sensors for the next generation of rehabilitation robotics

ANSELMO FRIZERA, PHD

FEDERAL UNIVERSITY OF ESPIRITO SANTO (BRAZIL)

UNIVERSIDADE FEDERAL DO ESPÍRITO SANTO

Summary

Introduction and motivation

Part I. Introduction to soft robotics and rehabilitation systems

Part II. Optical fiber sensing

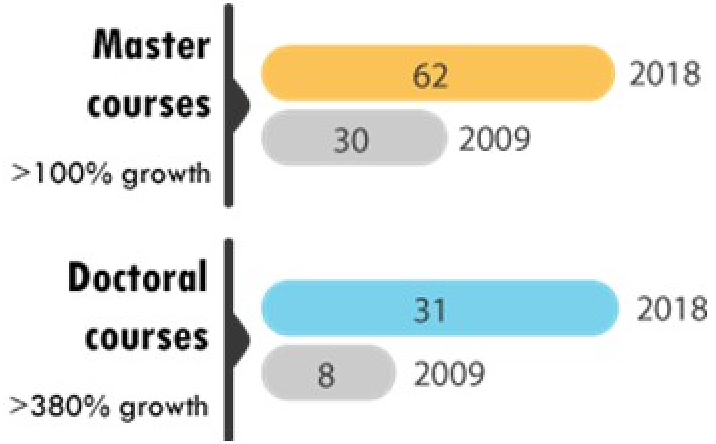
Part III. Optical fiber sensors in rehabilitation systems

Conclusions and final remarks

UFES in numbers

Staff & Students:

- Professors: 1,700+
- Administrative: 1,900+
- Undergraduate students: 20,400+
- Graduate students: 4,000+

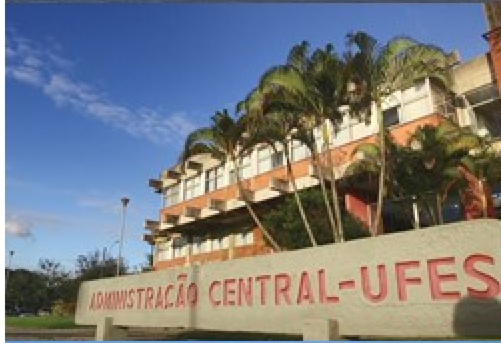


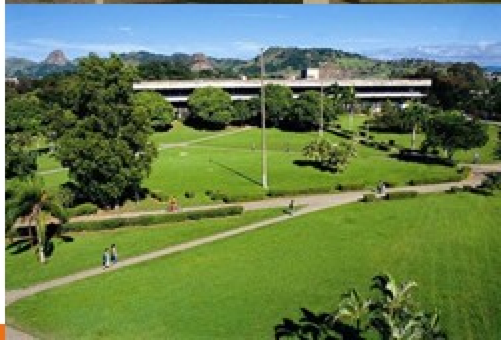
Ranking positions (Engineering):

- #8 in Brazil
- #19 in Latin America
- #60 in Iberoamerica

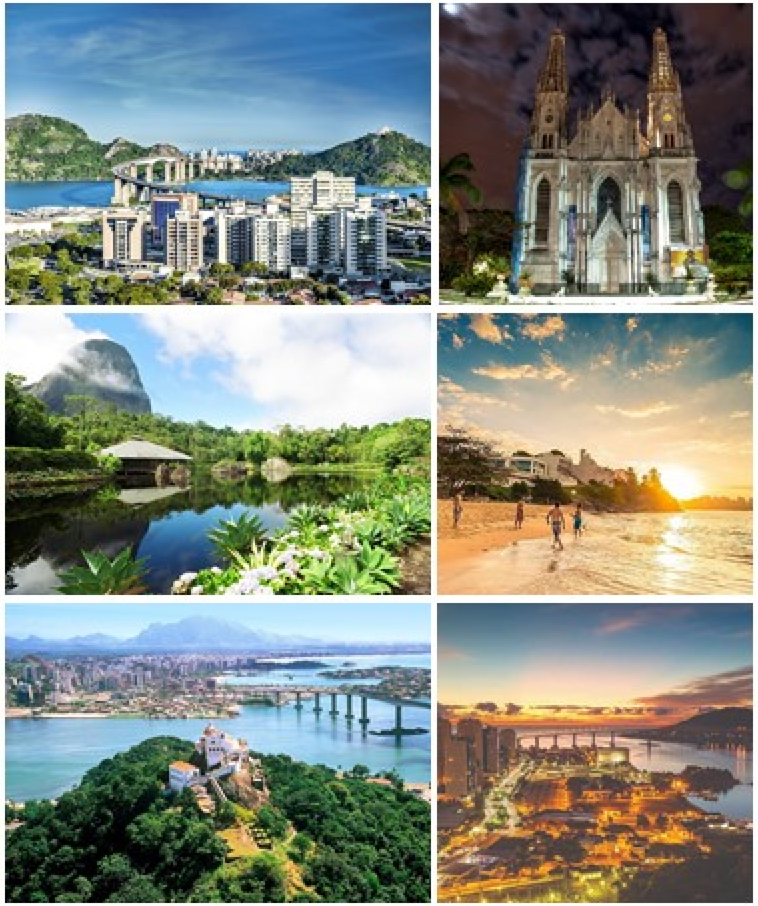
SCIMAGO

THE WORLD UNIVERSITY RANKINGS





Vitória – Espírito santo (Brazil)



Brief CV

2001 - 2006
Electrical Engineering

2006 - 2010
Predoctoral fellow &
PhD in Electronics

2010 - Present
Professor

2014 - 2018
Member of the Board

2014 - Present
Fellow

2016 & 2018
Visiting Professor

2017 & 2018
Visiting Professor

2020
IEEE Impact Creator

2021
IEEE/EMBS
- Distinguished Lecturer
- Student Mentor

2022
IEEE Senior Member

Conditions that Affect Mobility

STROKE

A leading cause of disability in the developed world.

Reduced gait speed, shortened step length & loss of balance and often experience falls.

SPINAL CORD INJURY

Over 130,000 people each year survive a traumatic SCI (bound to a wheelchair).

Maximization of user independence & mobility are the main objectives.

CEREBRAL PALSY

CP is the most common cause of permanent serious physical disability in childhood.

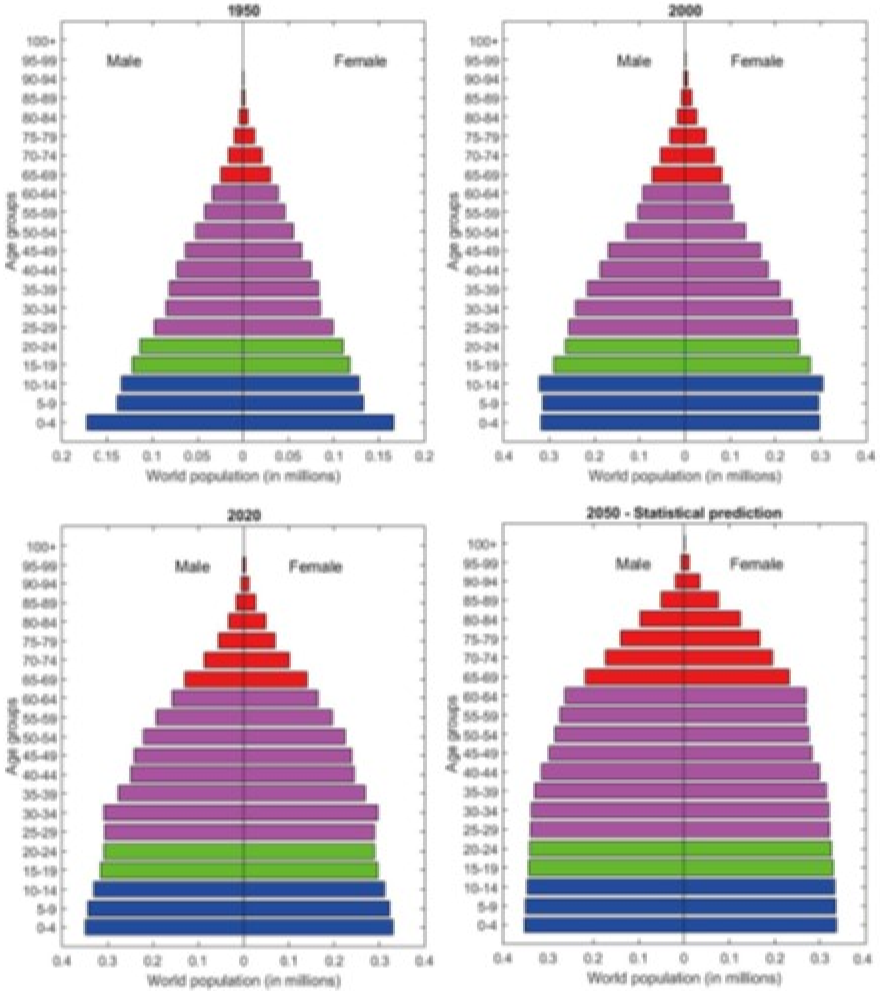
Survival in children with severe level of impairment has increased in recent years.

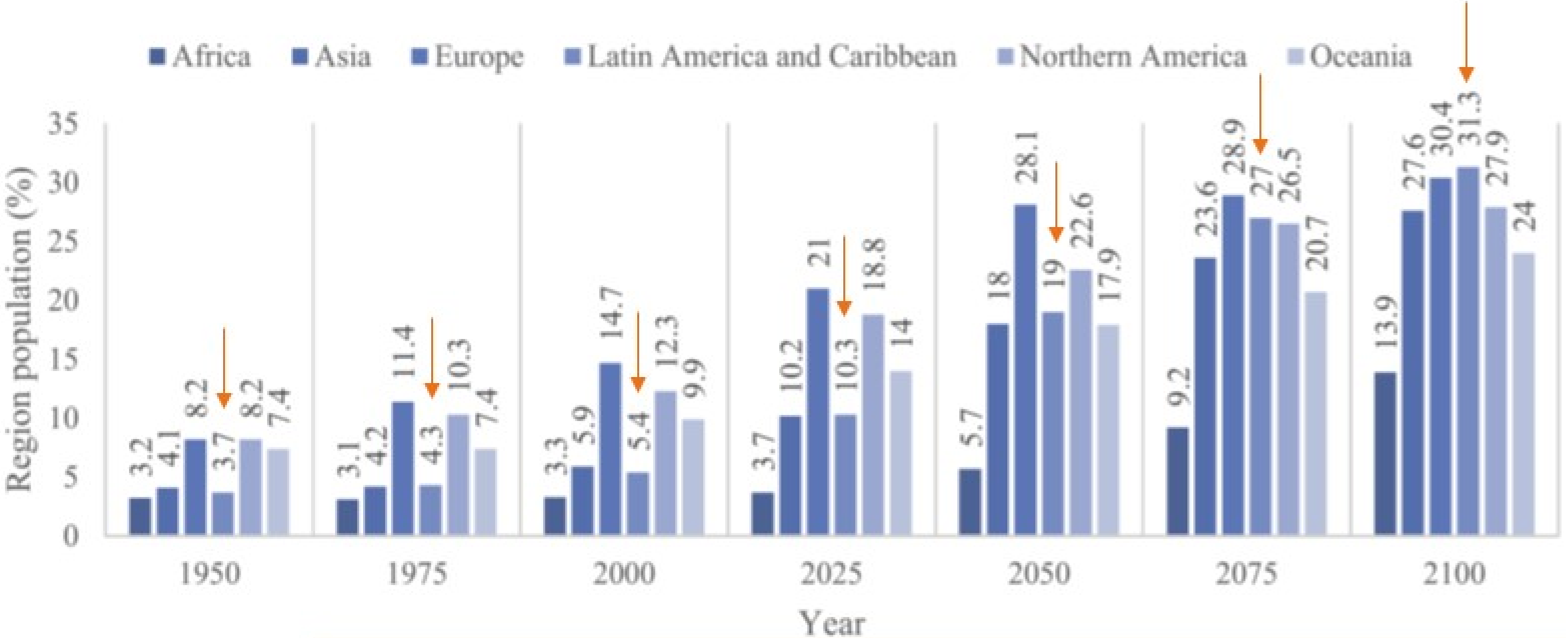
ELDERLY POPULATION

Less developed countries (1.7 billion 2050) Worldwide (2 billion-2050)

It includes cardiovascular conditions, dementia, diabetes, arthritis, osteoporosis and stroke.

Elderly Population: Latin America and Caribbean





How are we going to react to such change in our population?

- Rehabilitation? Physical therapy?
  - Many regions report shortage in physiotherapists and rehabilitation personnel.
  - High-income countries: ~ 5 physiotherapists per 10,000 population
  - This number is even lower for low-income regions

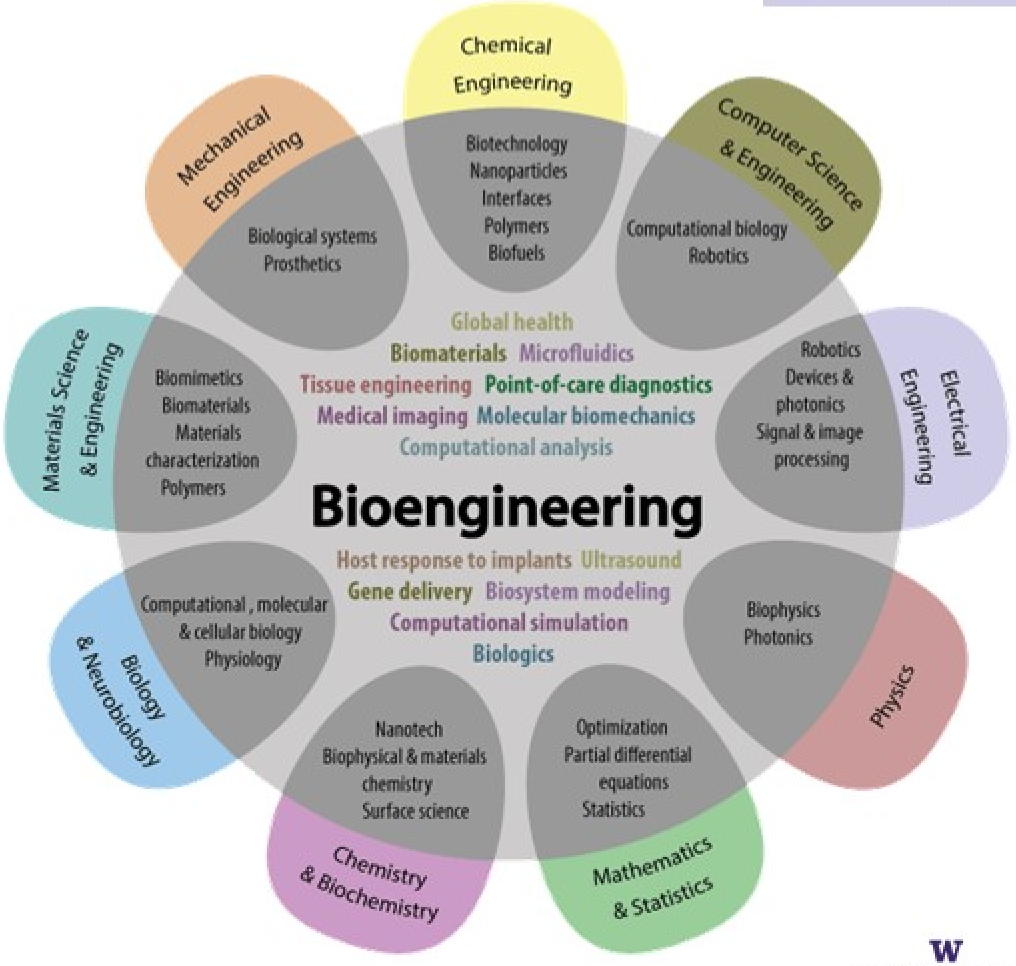
Biomedical Engineering

The application of engineering principles and design concepts to medicine and biology for healthcare purposes (e.g. diagnostic or therapeutic).

Biomedical engineering education must allow engineers:

- To analyze a problem from an engineering and biological perspective
- To anticipate the special difficulties in working with living systems and
- To evaluate a wide range of possible approaches to solutions.

Robotics
Devices & photonics
Signal & Image Processing



JOHNS HOPKINS
BIOMEDICAL ENGINEERING

Part I. Introduction to soft robotics and rehabilitation systems

- Introduction and overview of wearable technologies
- Soft wearable robots & enabling technologies

Robotics & Automation

Automation
- Applications and control paradigms
- No need for human intervention

Robotics
- Robust robotic machines
- Predefined tasks
- No physical interaction
- Dangerous environment for humans

New Robotic Applications
- Cleaning robots
- Automatic management and sorting in warehouses
- ...
- Rehabilitation Robots

Human and Robots
- Efficient workforce
- Effective and innovative goals
- Higher dexterity:
  - Control systems
  - Robots’ design

Soft Matter to Build Robots

Robots are expected to be seen in many tasks that involve direct contact and interaction with humans

Soft robotics:

- A growing research field
- Born by the combination of robotics and soft materials and textiles
- Pushing the use of robots to new limits, applications and environments

Benefits:

- Energy absorption for stability
- Physical robustness
- Human safe operation
- Embodied intelligence
- Low-cost fabrication techniques

Soft Robots
biomedical applications

Soft tools for surgery

Drug delivery

Wearable devices

Assistive technologies

Prostheses

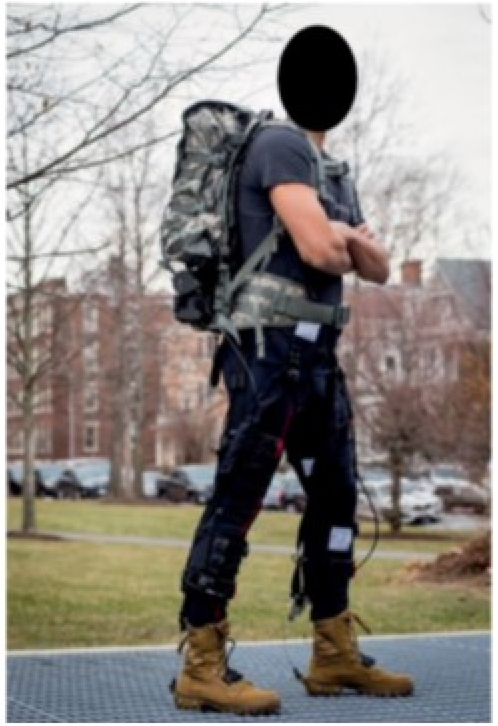
Artificial organs

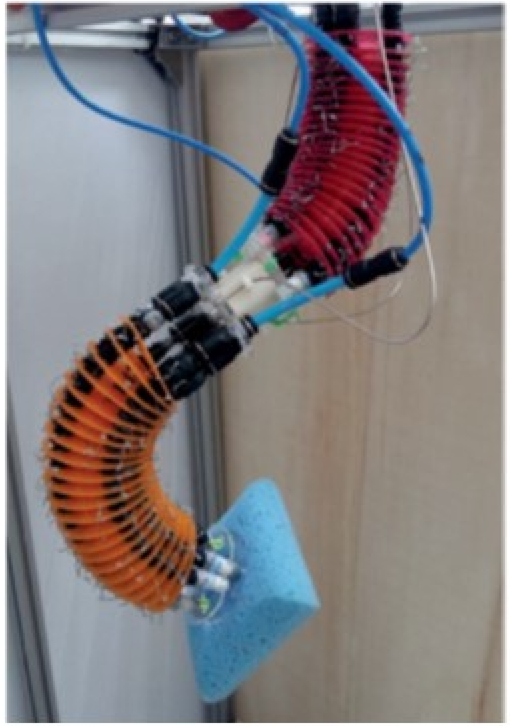
Active body simulators for training and biomechanical studies

Soft Robots
biomedical applications

Wearable devices

Assistive technologies





Assistive Devices

From passive instruments and structures for joint stabilization and support

To **<u>complex and automated solutions</u>** (including wearable robotic devices)

Rigid robotics → restoring motor functions:

- Restoring ambulatory walking
- Delivering body weight support
- Gait rehabilitation and assistance
- Upper limb rehabilitation
- Tremor suppression, ...

Consistent and intensive recovery therapies over longer periods, regardless of the therapist's fatigue level



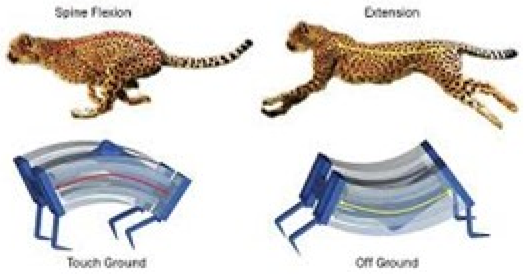


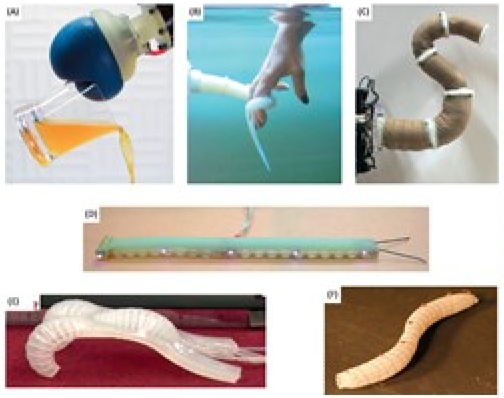


The Role of Bioinspiration

- Rigid link devices
  - Robots inspired by animals with hard skeletons
  - Require meticulous programming and extensive feedback to avoid collisions and dangerous situations

- Soft robots
  - Elastic/moldable materials that can adapt to their surroundings
  - Closer & safer human-robot interaction
  - Novel compliant actuators
  - Enhanced compliance
  - Higher controllability
  - Smaller impact energy (in case of accidents and unintended contacts)





Soft Robots for Rehabilitation and Functional Compensation

Natural and important evolution of exoskeletal robotic devices

- Compliant
- Low weight & low profile
- Safe interaction

Eliminating the need of precisely aligning the robot and biological joints:

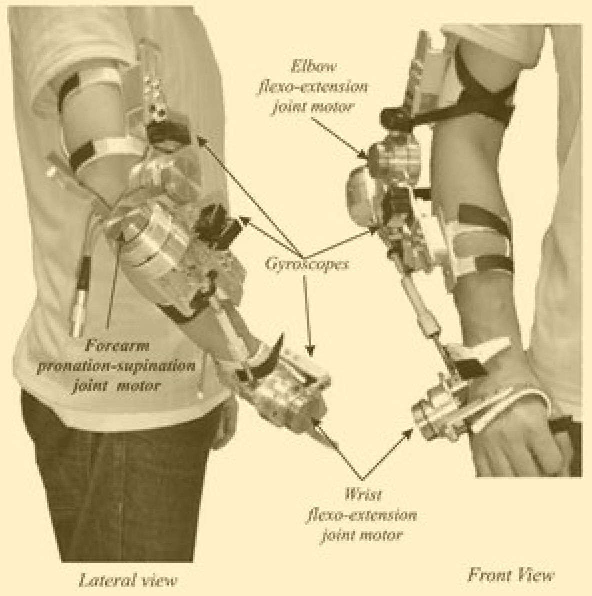
- Safe and effective human-robot interaction
- Avoid Macro and Micro-misalignments

Areas of research/interest:

- Materials science, robotics, and medical research

Avoiding interference with the natural motion of the user

- Decreasing energy consumption
- Avoiding disrupting natural biomechanics of walking or causing discomfort



Are soft robots a universal solution?

Lack of external rigid structures may impact on applications that require:

- (full) Body weight support for locomotion
- Load carriage (avoid overloading the wearer's joints)

Enabling Technologies:
sensors, actuators & materials

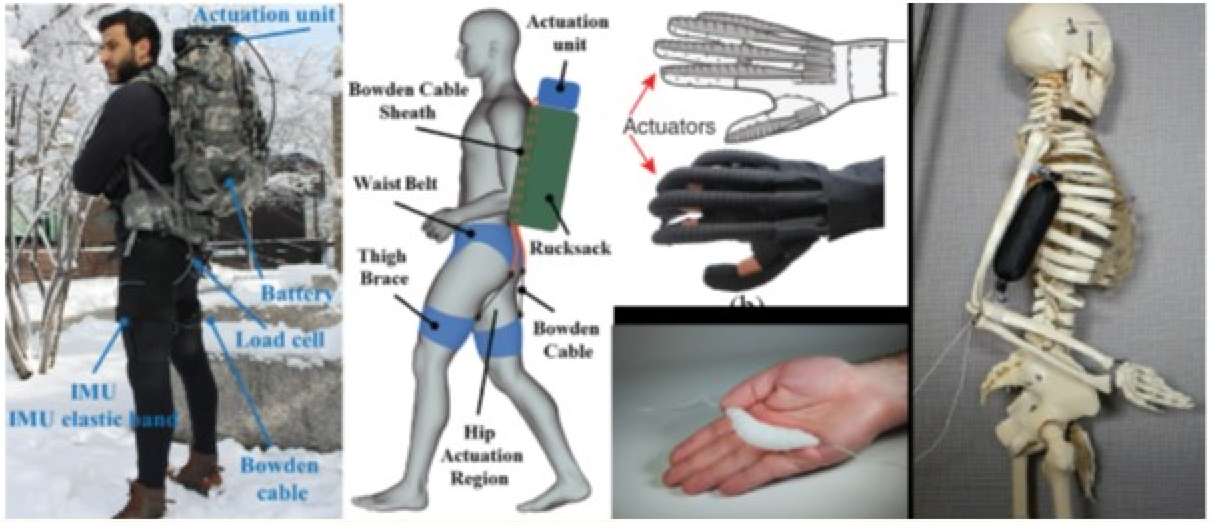
Incorporation of soft sensors and use of soft materials:

- Functionality, performance, comfort, and usability

Challenges:

- Actuation
- Sensing
- Control

To achieve actual benefits to the users



Enabling Technologies: sensors

Flexible sensors are used to provide a feedback on the actuator's states

Stretchable electronics:
- Resistive and capacitive sensors in soft structures
- Different substrates can be used to achieve higher flexibility of the sensors

Flexible piezoresistive materials:
- Pressure and force sensing

Magnetic sensors
- Kinematics assessment in soft robotics (Rus and Tolley, 2018)

Optoelectronic sensors:
- Low-cost approaches (such as the light intensity variation)
- Used in in stretchable materials with different geometries

Enabling Technologies: optical fiber sensors

Enhance the performance of the integrated structures

Intrinsic advantages:

- Electromagnetic field immunity, galvanic isolation, multiplexing capabilities and small dimensions

Embedment of optical fibers in the 3D printed structures

- Integrated solutions
- Optical fibers can be fabricated directly from the 3D printers
- Dimensions and properties can be optimized for each application or for each user.

Higher resolution and accuracy when compared with conventional electronic sensors

Part II. Optical fiber sensing

Introduction to optical fiber sensing

Optical fiber materials

Optical fiber sensing technologies

Optical Fiber Sensors

Small size and weight

Multiplexing capabilities

Cost effective

Low transmission losses

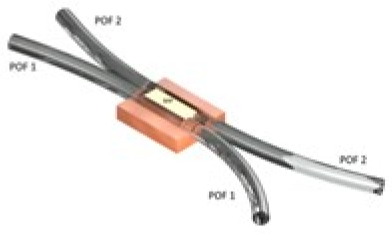
Immunity to electromagnetic interferences

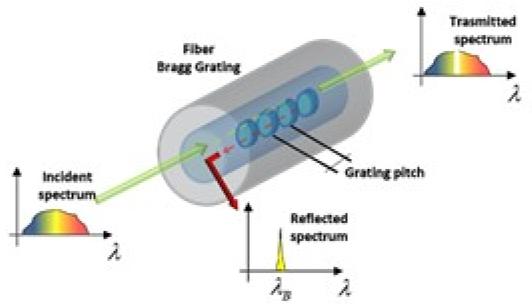
No sparks / explosion (intrinsic safety)

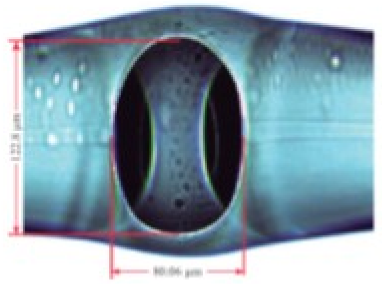
Chemically stable

Technologies & Operation Principles

- Fiber Bragg Gratings
- Intensity modulation (POF) sensors
- Interferometric Sensors
- Non-linear effects
- ...







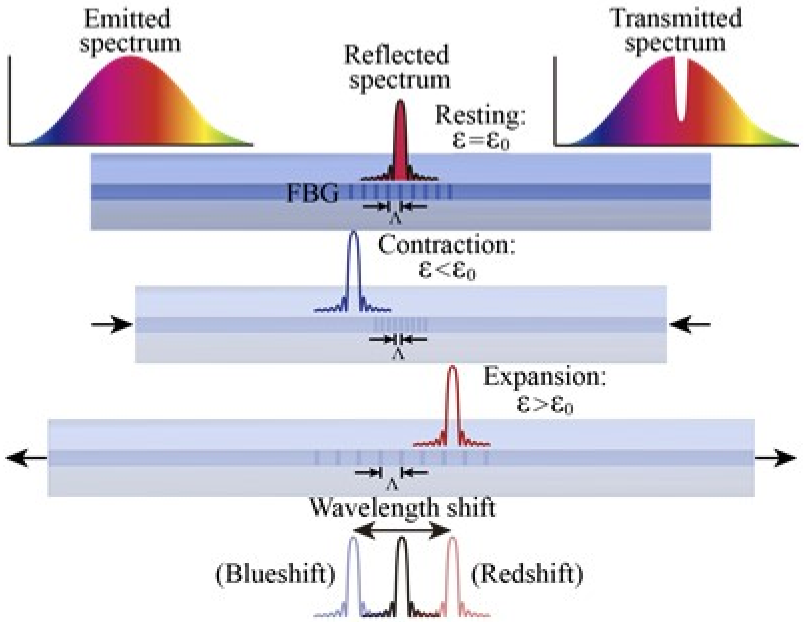
Fiber Bragg Gratings (FBG)

Advantages:

- Multiplexing
- Robustness
- Temperature and strain are directly obtained

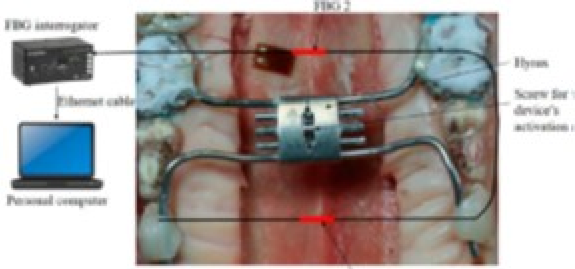
Many applications:

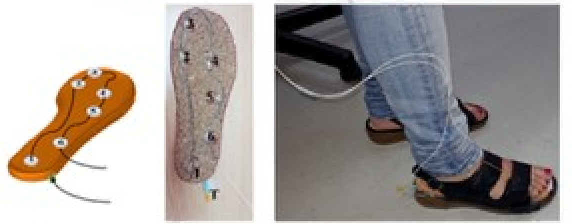
- Orthodontics
- Monitoring physiological signals
- Biomechanics
- Microclimate

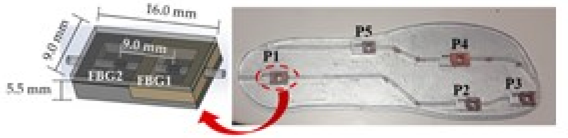


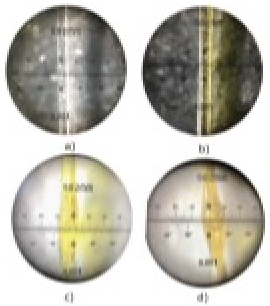
$$\Delta\lambda_B = \lambda_B[(1 - p_e)\varepsilon + (\alpha + \xi)\Delta T]$$

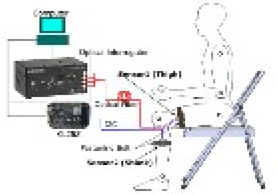
- $\Delta\lambda_B$: Bragg wavelength variation
- p_e: photo-elastic coefficient
- α: thermal expansion coefficient
- ξ: thermo-optic coefficient

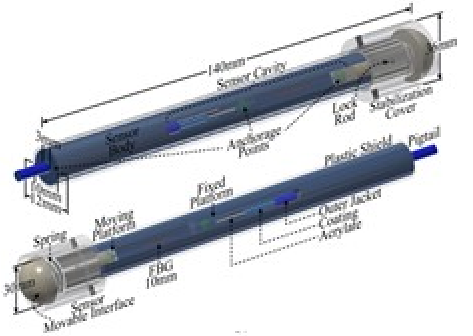












POF Sensors

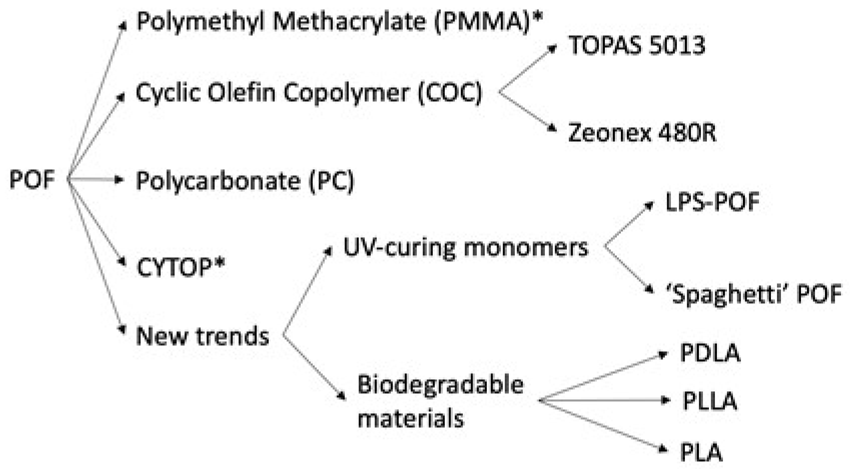
Additional advantages:

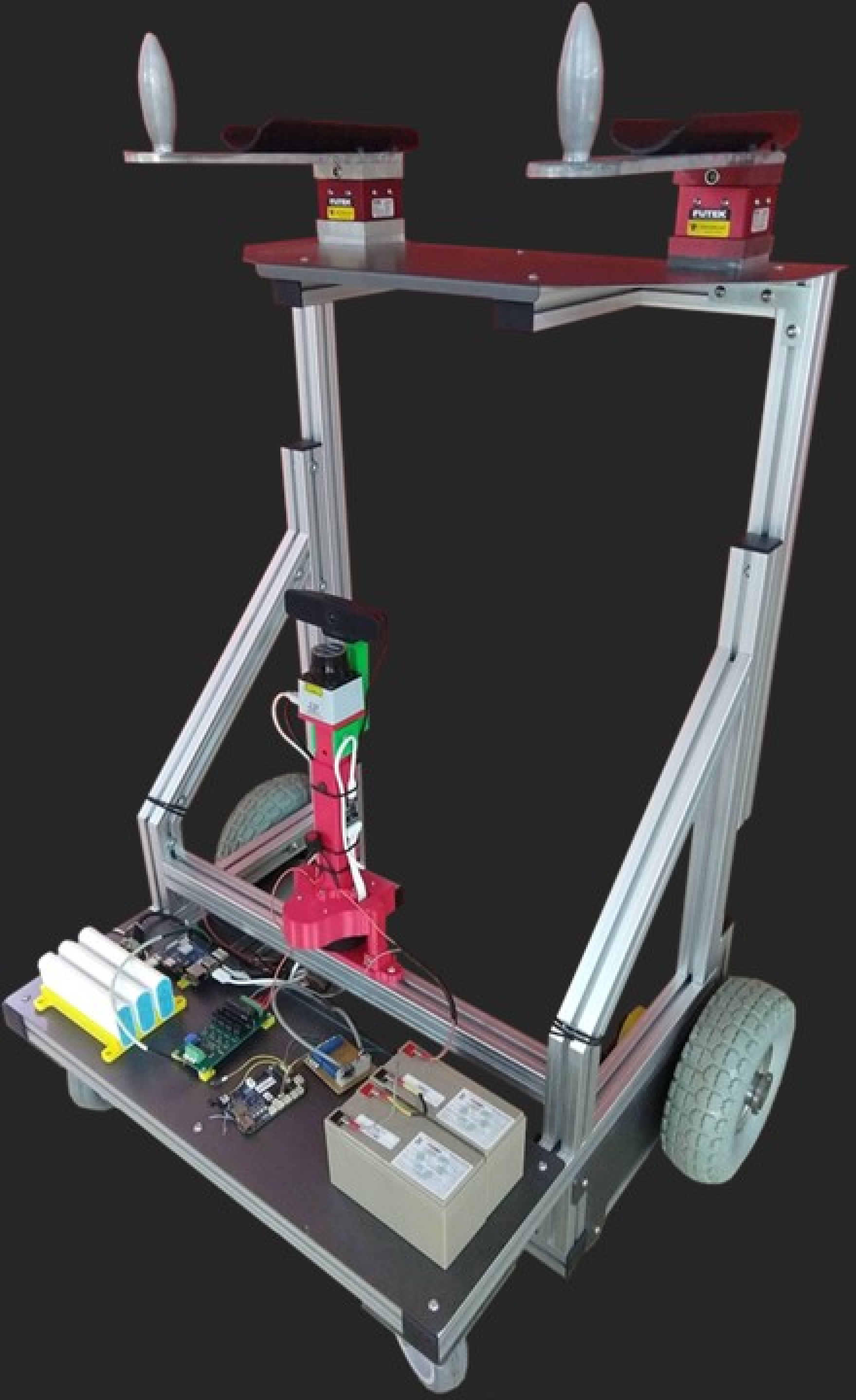
- Easier and low-cost setups due to superior dimensions
- New materials
- Inexpensive core material (PMMA)
- Mechanical resilience and elasticity
- Low impact by dust and water

Working principles:

- Modulation of intensity
- Phase shift
- FBG
- Chemical sensors, …

Materials:





Part III. Optical fiber sensors in rehabilitation systems

Optical fiber sensors for:

- Rehabilitation robotics
- Biomechanics and health monitoring
- Balance assessment protocols

Optical Fiber Sensors for Rehabilitation Robotics

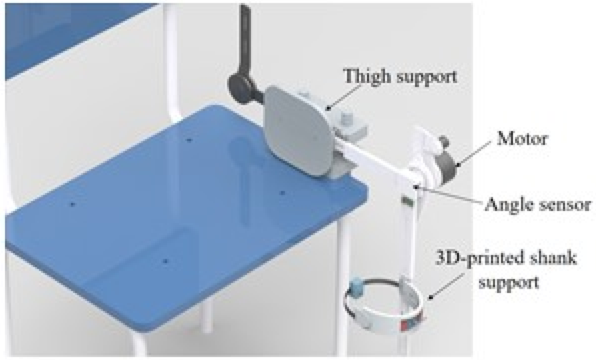
Gait assistance - Exoskeletons

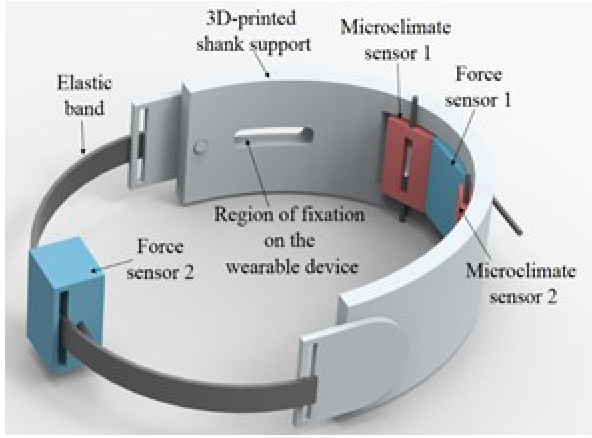
Exoskeletons
Smart walkers
Prosthetics

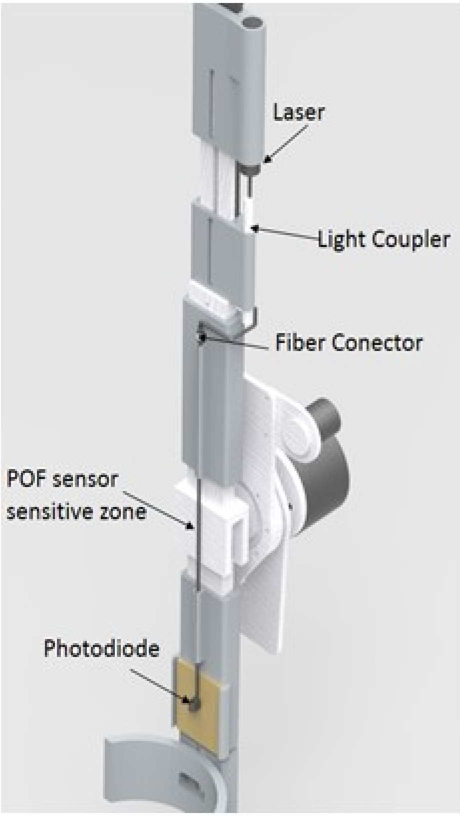
Measured parameters

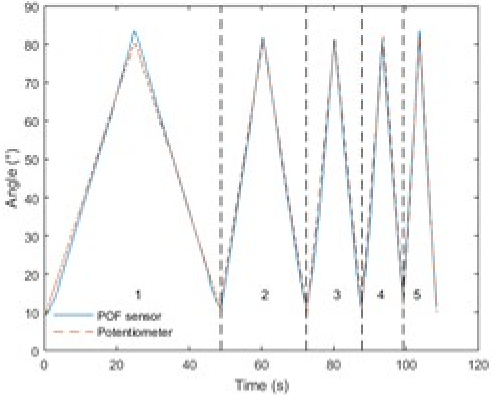
- Angles/torques in wearable robots
- Actuator dynamics
- User's movement intention
- Human-robot interaction forces
- Robot-environment interaction
- Environment mapping
- Microclimate sensing

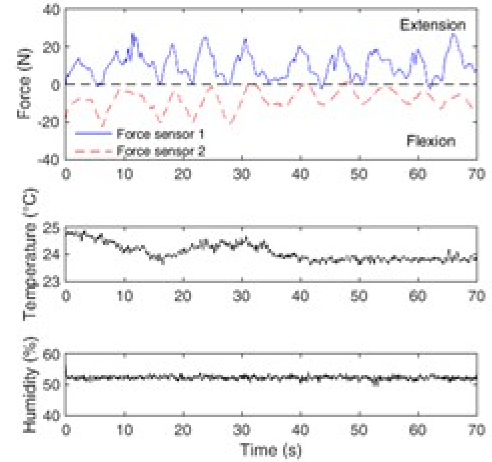
Intensity variation POF Sensors











Leal-Junior, A.G.; Díaz, C.R.; Pontes, M.J.; Marques, C.; Frizera, A. Polymer optical fiber-embedded, 3D-printed instrumented support for microclimate and human-robot interaction forces assessment. *Opt. Laser Technol.* 2019, *112* 323–331.
Leal-Junior, A.G.; Frizera-Neto, A.; Pontes, M.J.; Botelho, T.R. Hysteresis compensation technique applied to polymer optical fiber curvature sensor for lower limb exoskeletons. *Meas. Sci. Technol.* 2017, *28*, 125103.

Optical Fiber Sensors for Rehabilitation Robotics

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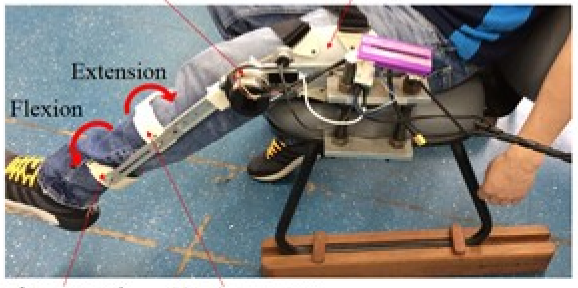
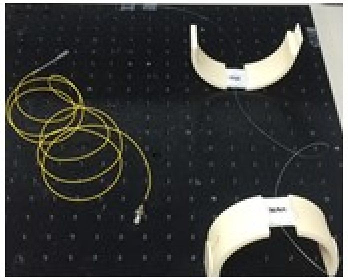
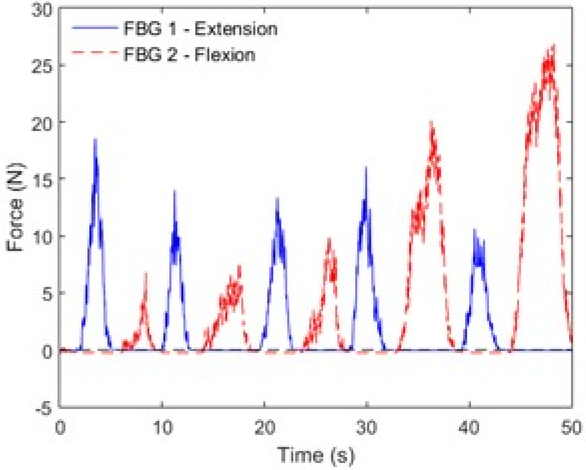
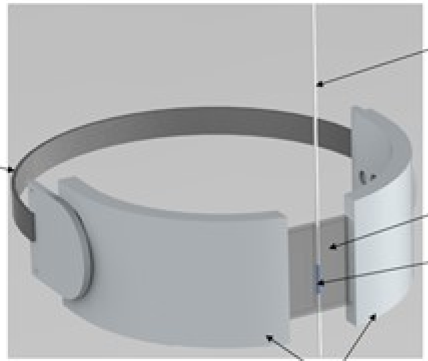
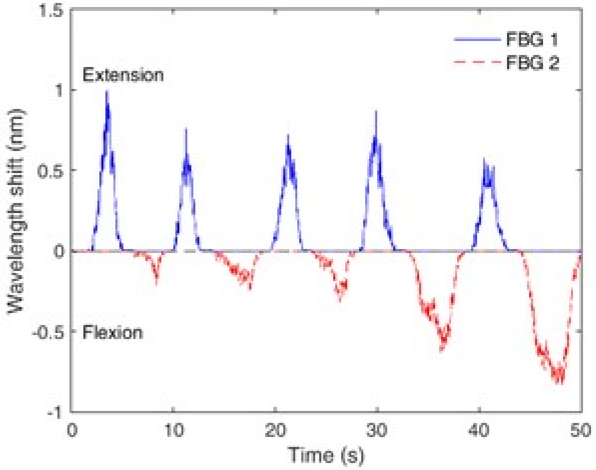
FBG Sensors











1. Leal-Junior, A.; Theodosiou, A.; Díaz, C.; Marques, C.; Pontes, M.; Kalli, K.; Frizera-Neto, A. Fiber Bragg Gratings in CYTOP Fibers Embedded in a 3D-Printed Flexible Support for Assessment of Human–Robot Interaction Forces. Materials (Basel). 2018, 11, 2305.

Optical Fiber Sensors for Rehabilitation Robotics

Other Developments

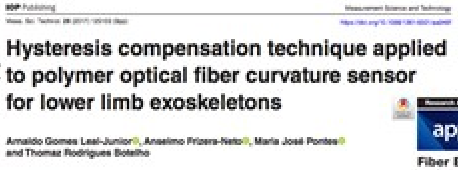
Casas, J.; Leal-Junior, A.; Díaz, C.R.; Frizera, A.; Múnera, M.; Cifuentes, C.A. Large-range polymer optical-fiber strain-gauge sensor for elastic tendons in wearable assistive robots. Materials (Basel). 2019, 12.


Optics and Laser Technology

Full length article

Analytical model for a polymer optical fiber under dynamic bending

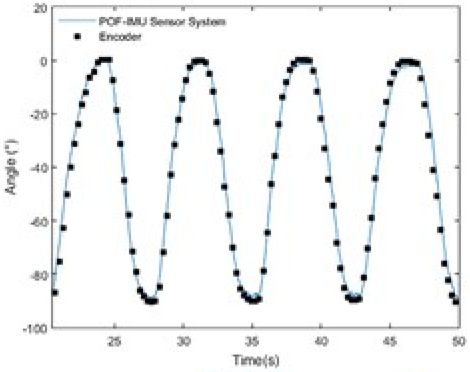
Arnaldo G. Leal Junior, Anselmo Frizera, Maria José Pontes

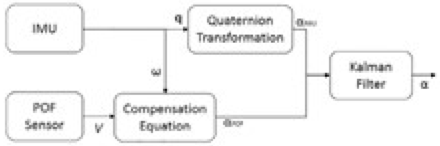

Hysteresis compensation technique applied to polymer optical fiber curvature sensor for lower limb exoskeletons

Arnaldo Gomes Leal-Junior, Anselmo Frizera-Neto, Maria José Pontes and Thomaz Rodrigues Botelho


applied optics

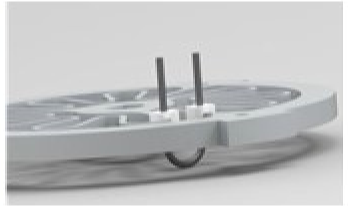
Fiber Bragg grating-based sensor for torque and angle measurement in a series elastic actuator's spring

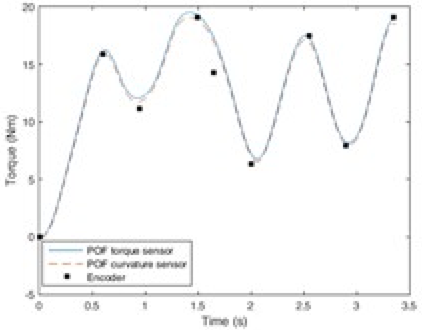


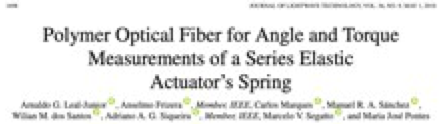



Optical Fiber Technology

POF-IMU sensor system: A fusion between inertial measurement units and POF sensors for low-cost and highly reliable systems






Polymer Optical Fiber for Angle and Torque Measurements of a Series Elastic Actuator's Spring

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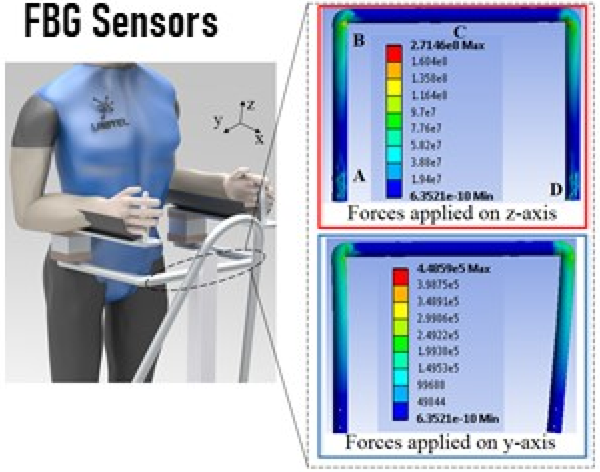
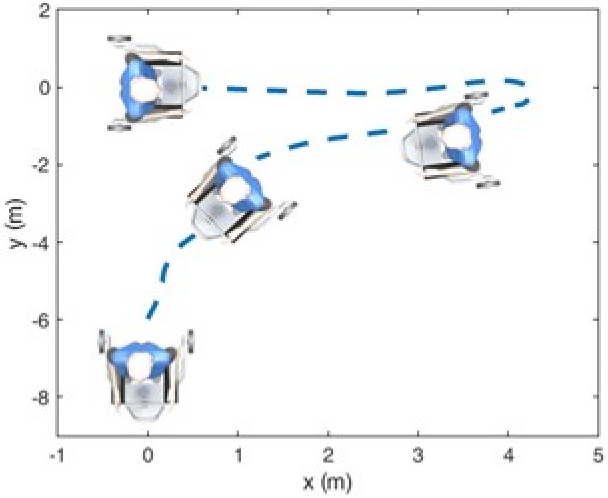
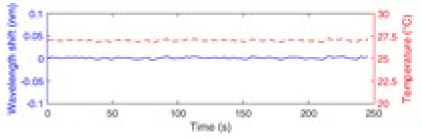
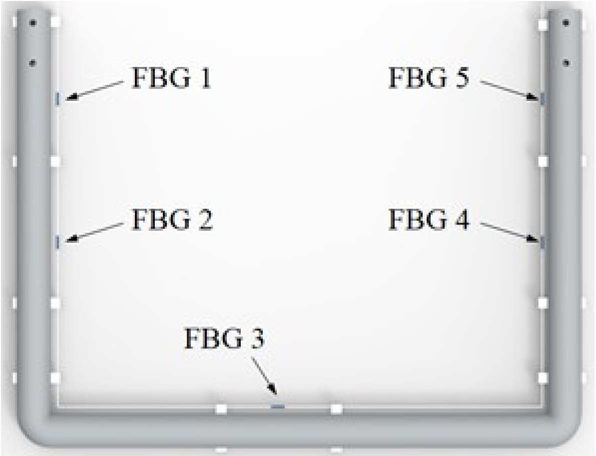
- Microclimate sensing

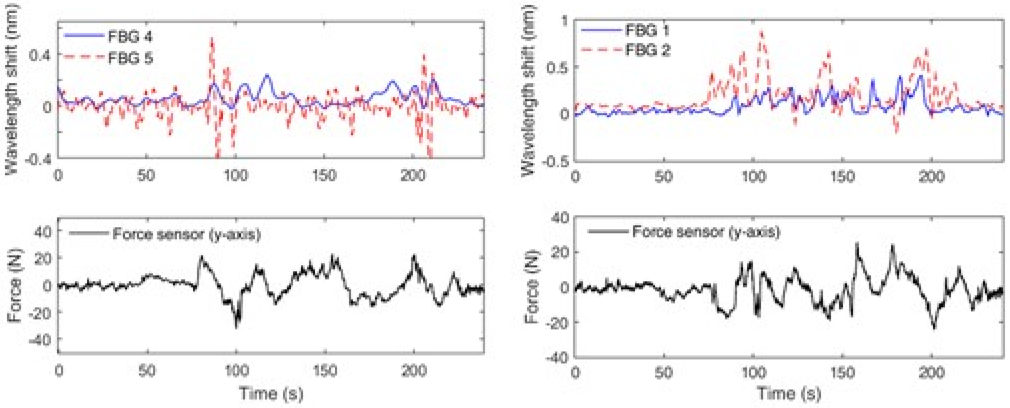
FBG Sensors











Leal-Junior, A.G.; Frizera, A.; Theodosiou, A.; Diaz, C.; Jimenez, M.; Min, R.; Pontes, M.J.; Kalli, K.; Marques, C. Plane-by-Plane Written, Low-Loss Polymer Optical Fiber Bragg Grating Arrays for Multiparameter Sensing in a Smart Walker. IEEE Sens. J. 2019, 1748, 1-1

Optical Fiber Sensors for Rehabilitation Robotics

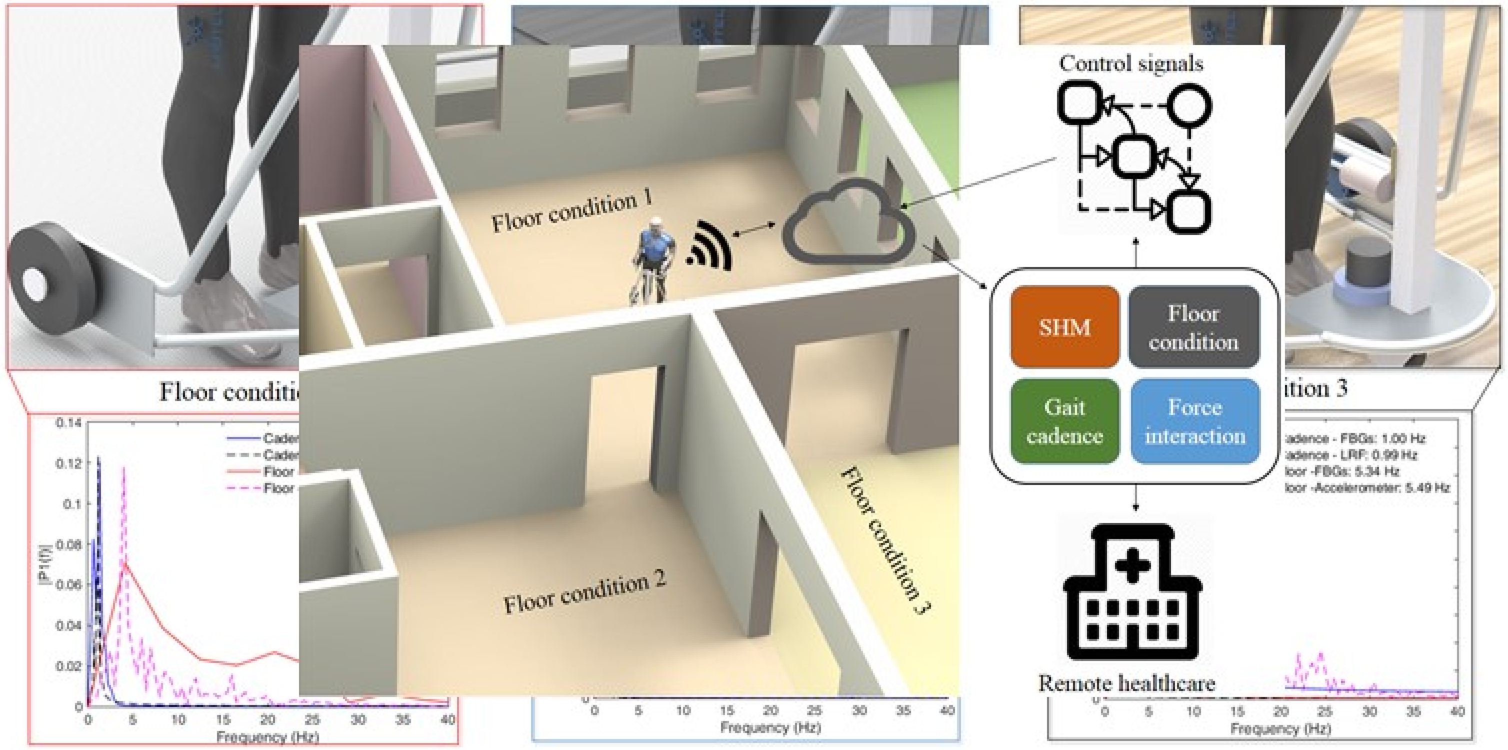
Gait assistance – Smart Walkers

Exoskeletons
Smart walkers
Prosthetics

Measured parameters

- Angles/torques in wearable robots
- Actuator dynamics
- User's movement intention
- Human-robot interaction forces
- Robot-environment interaction
- Environment mapping
- Microclimate sensing

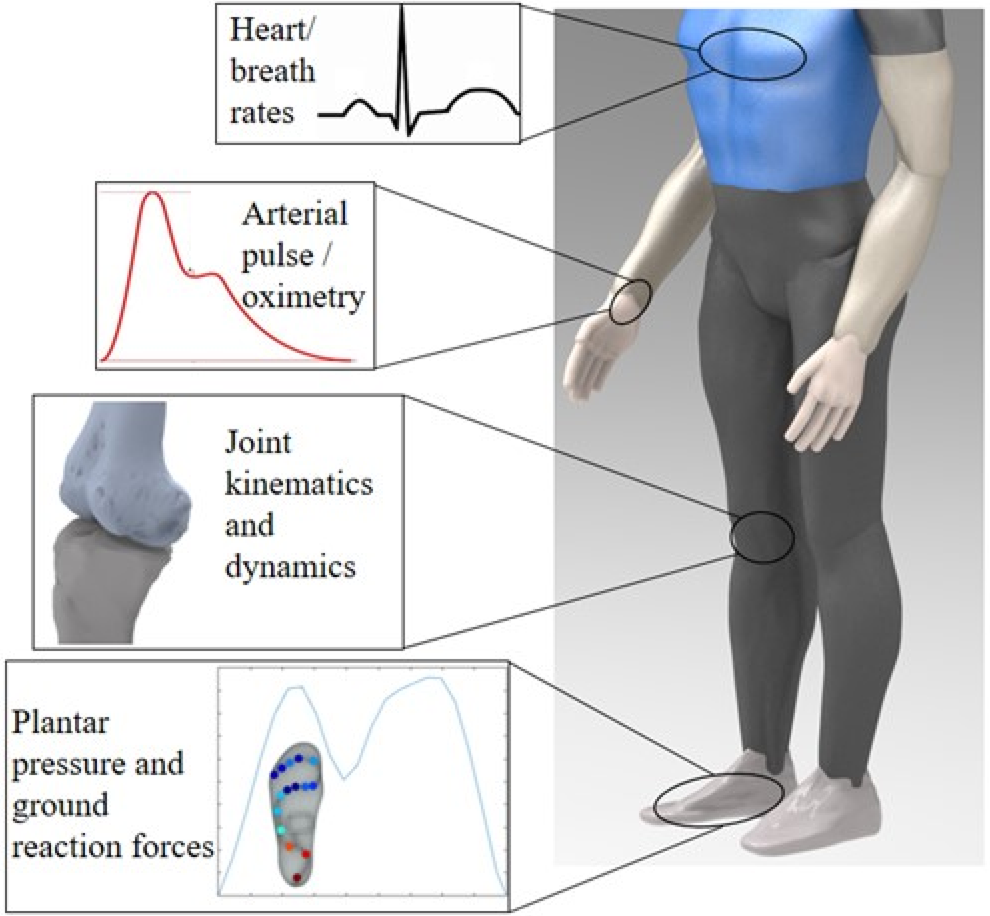
FBG Sensors



Leal-Junior, A.; Theodosiou, A.; Díaz, C.; Marques, C.; Pontes, M.; Kalli, K.; Frizera-Neto, A. Fiber Bragg Gratings in CYTOP Fibers Embedded in a 3D-Printed Flexible Support for Assessment of Human-Robot Interaction Forces. Materials (Basel). 2018, 11, 2305.

Biomechanics & Health Monitoring

Motivation



Patient's remote monitoring

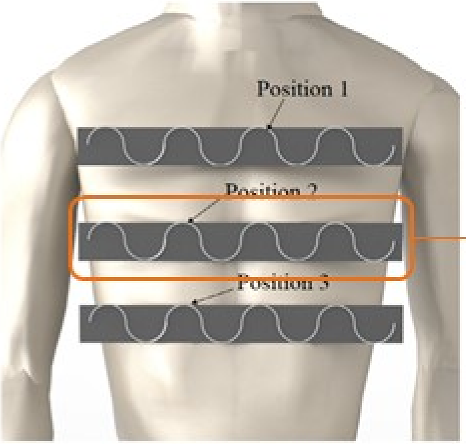
- Fall risk
- Chronic diseases
- Rehabilitation process

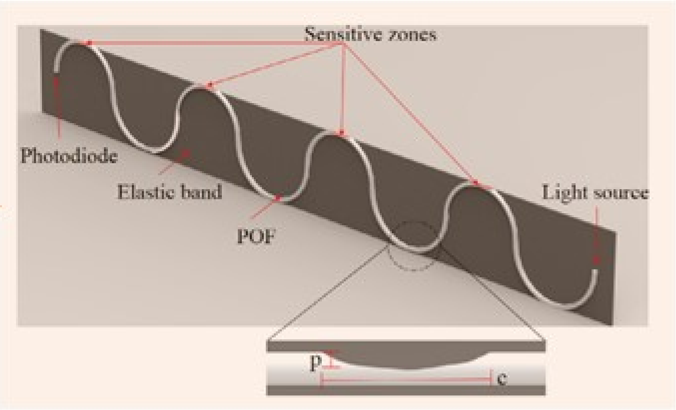
Measured parameters

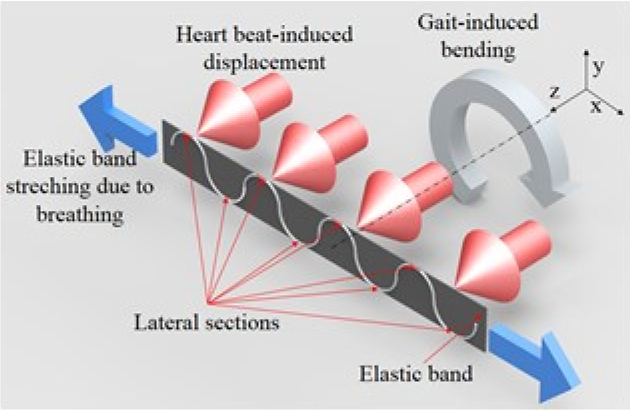
- Joint kinematics and dynamics
- Physiological parameters
- Human-environment interaction
- Plantar pressure mapping

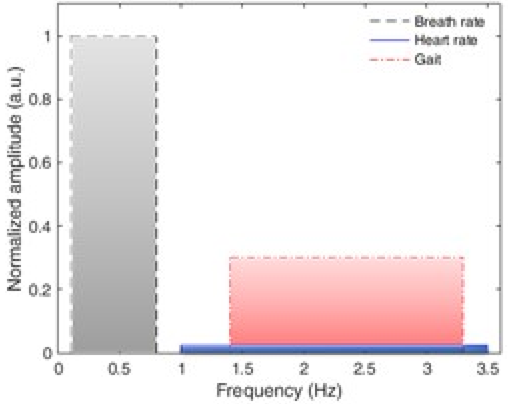
Biomechanics & Health monitoring

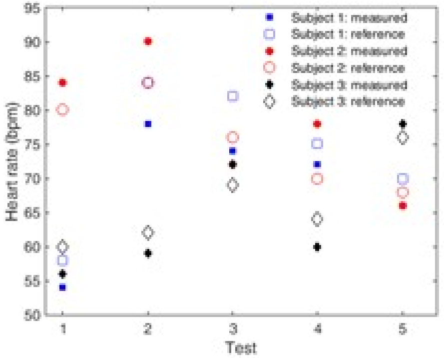
Smart textile for HR, breathing rate and gait cadence estimation

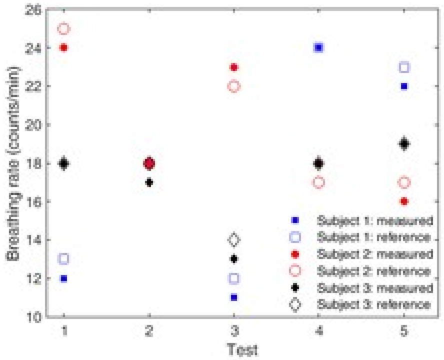


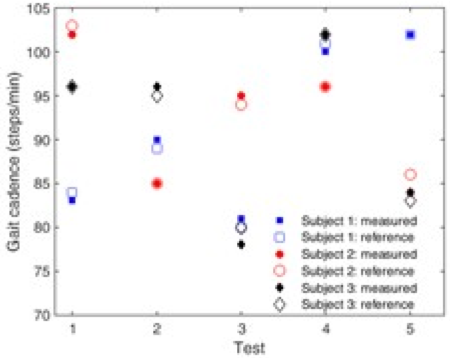


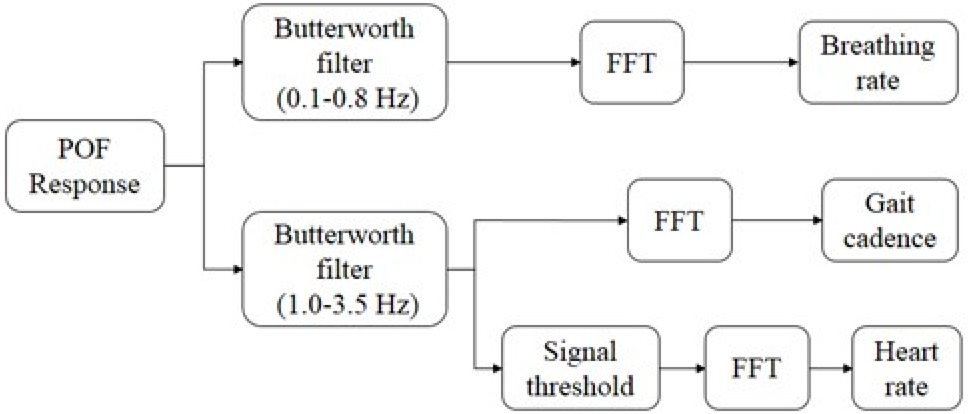








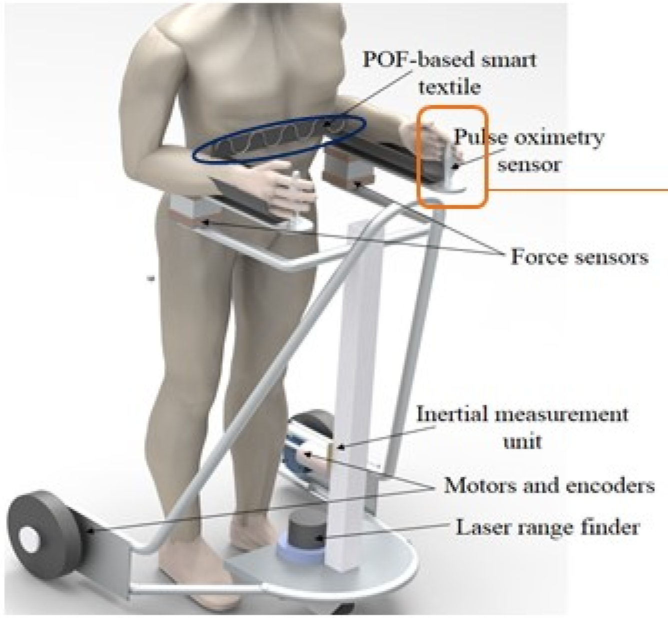




Leal, A.G.; Diaz, C.R.; Jimenez, M.F.; Leitao, C.; Marques, C.; Pontes, M.J.; Frizera, A. Polymer Optical Fiber Based Sensor System for Smart Walker Instrumentation and Health Assessment. *IEEE Sens. J.* 2018, *1748*, 1–1.

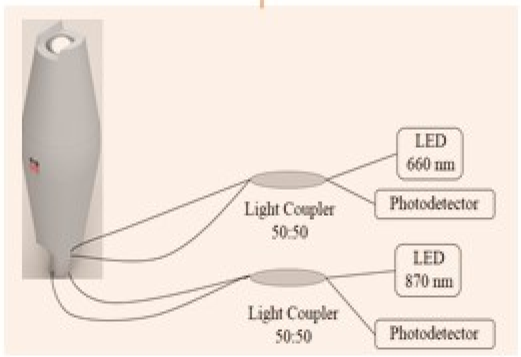
Biomechanics & Health monitoring

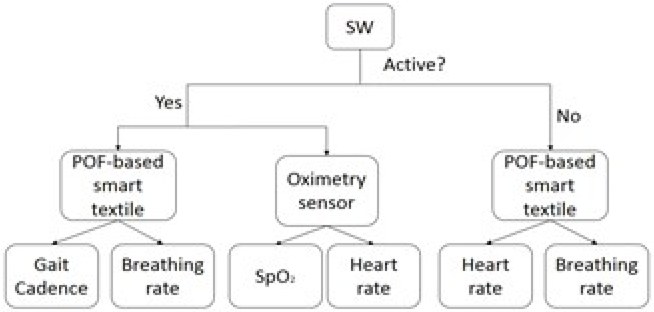
Smart Walker Instrumentation and Health Assessment

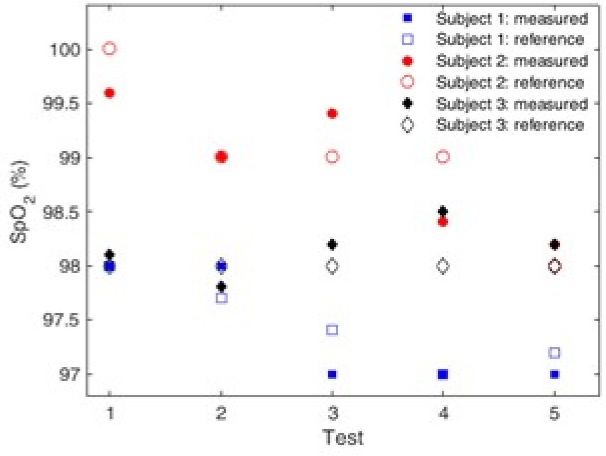


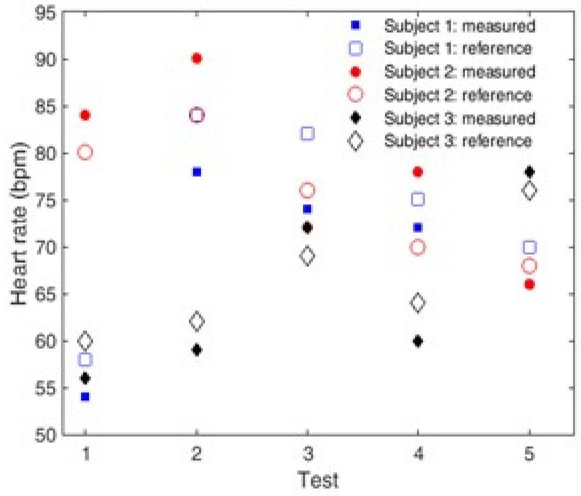
$$HbO_2 = (0.12\Delta P_{660nm} - 0.67\Delta P_{870nm})$$
$$Hb = (-0.17\Delta P_{660nm} + 0.14\Delta P_{870nm})$$

$$SpO_2 = \frac{HbO_2}{HbO_2 + Hb}$$





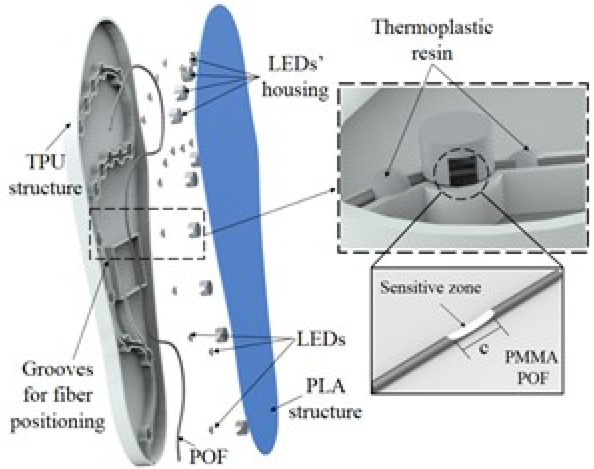


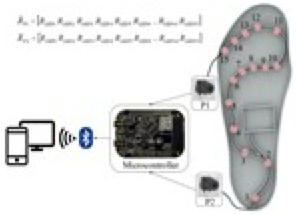


Leal, A.G.; Diaz, C.R.; Jimenez, M.F.; Leitao, C.; Marques, C.; Pontes, M.J.; Frizera, A. Polymer Optical Fiber Based Sensor System for Smart Walker Instrumentation and Health Assessment. *IEEE Sens. J.* 2018, *1748*, 1–1.

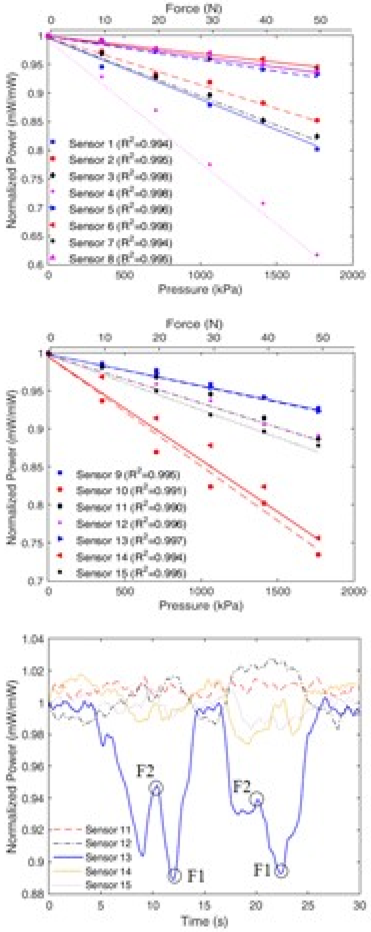
Biomechanics & Health Monitoring

Multiplexed intensity variation-based sensors for insoles

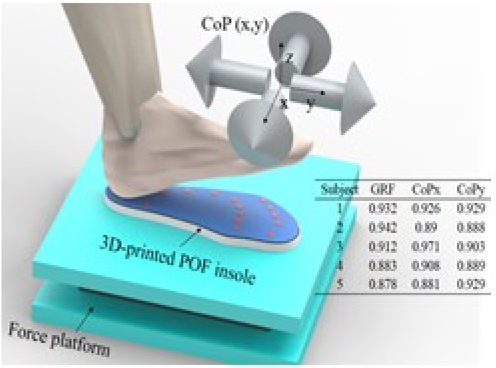




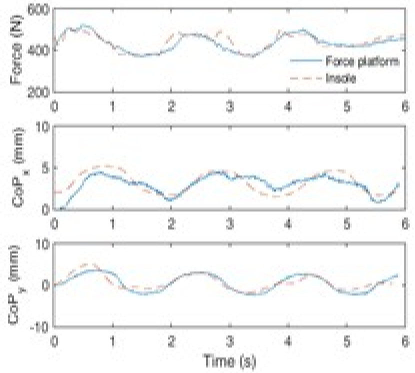
Sensor characterization



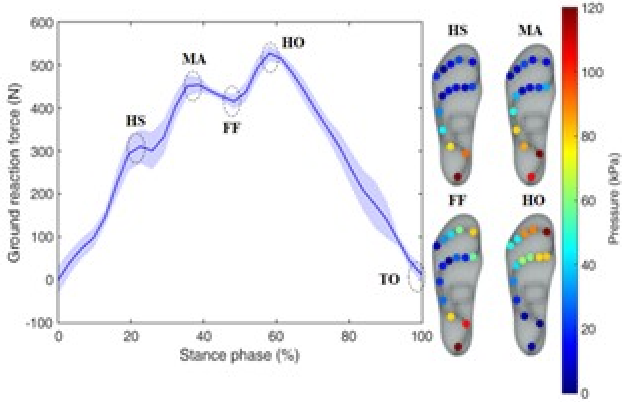
Validation on force platform

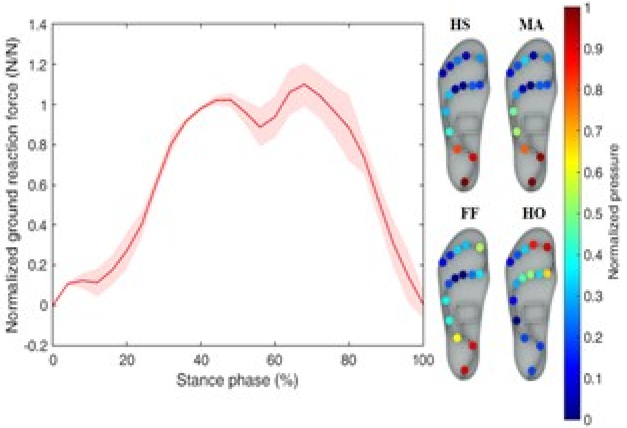


Subject	GRF	CoPx	CoPy
1	0.932	0.926	0.929
2	0.942	0.89	0.888
3	0.912	0.971	0.903
4	0.883	0.908	0.889
5	0.878	0.881	0.929



Gait analysis

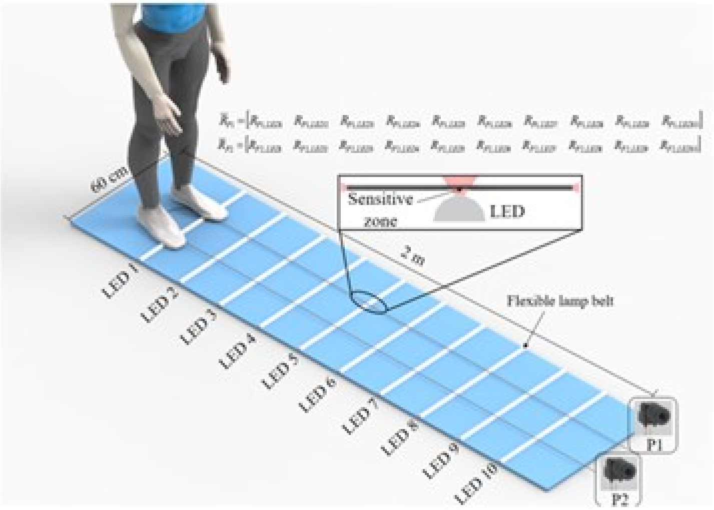




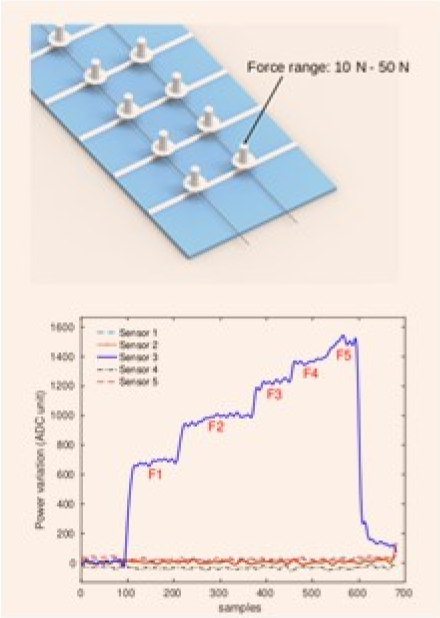
Leal-Junior, A.G.; Díaz, C.R.; Marques, C.; Pontes, M.J.; Frizera, A. Multiplexing technique for quasi-distributed sensors arrays in polymer optical fiber intensity variation-based sensors. *Opt. Laser Technol.* 2019, *111*, 81–88.

Biomechanics & Health monitoring

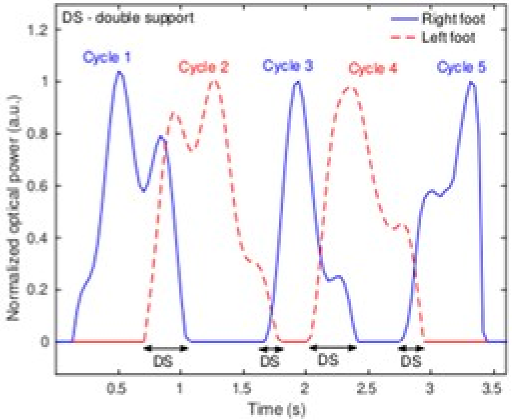
POF Smart Carpet



Force characterization



Ground Reaction Forces (GRF)

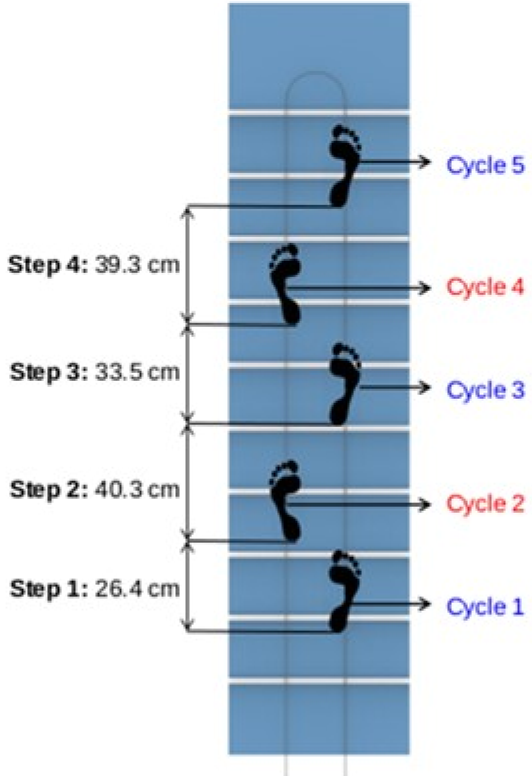


sensors
MDPI
Article

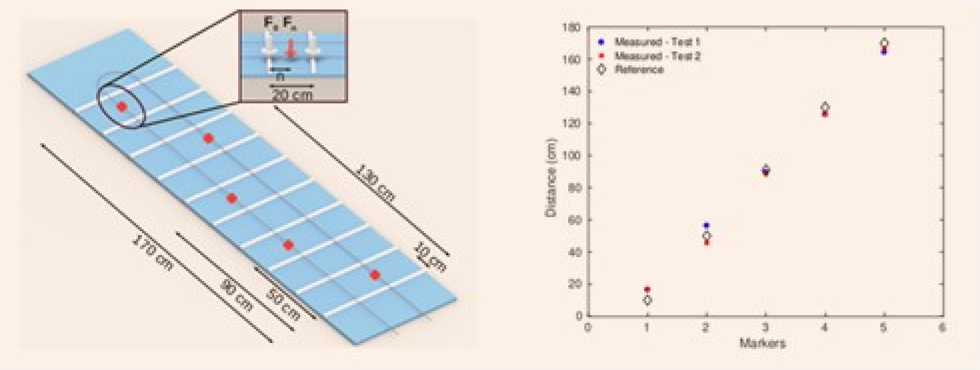
POF Smart Carpet: A Multiplexed Polymer Optical Fiber-Embedded Smart Carpet for Gait Analysis

Leticia M. Avellar [1,*], Arnaldo G. Leal-Junior [2], Camilo A. R. Diaz [1], Carlos Marques [3] and Anselmo Frizera [1]

1 Graduate Program in Electrical Engineering, Federal University of Espirito Santo, Vitoria 29075-910, Brazil
2 Mechanical Engineering Department, Federal University of Espirito Santo, Espirito Santo 29075-910, Brazil
3 I3N & Physics Department, University of Aveiro, Campus Universitário de Santiago, 3810-193 Aveiro, Portugal
* Correspondence: leticia.avellar@aluno.ufes.br; Tel.: +55-27-4009-2644



Position estimation

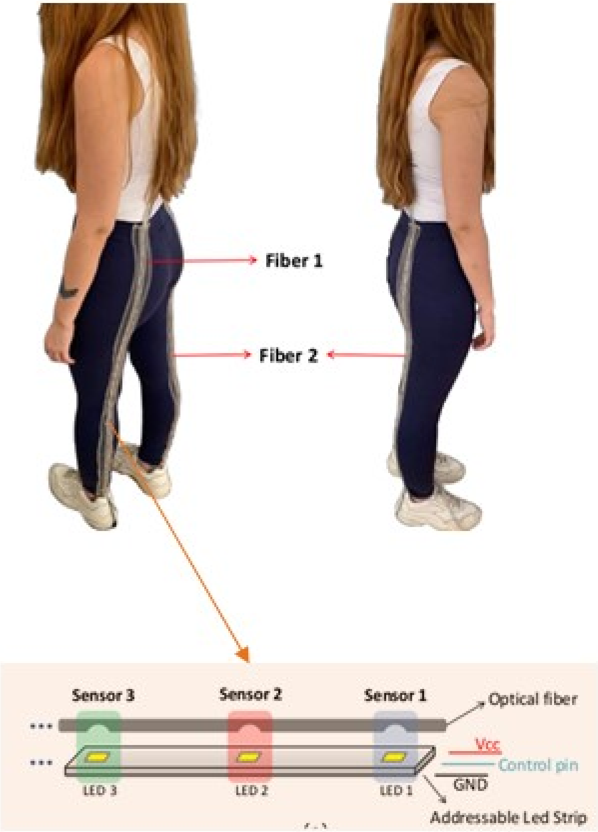


Spatio-temporal gait parameters

		Voluntary 1			Voluntary 2			Voluntary 3		
		T1	T2	T3	T1	T2	T3	T1	T2	T3
Step length (cm)	Step 1	26.4	42.9	16.5	46.5	35.2	30.3	56.5	39.5	38
	Step 2	40.3	31.9	56.9	35.5	35.6	51.1	31.0	35.2	31.1
	Step 3	33.5	42.1	48.1	27.0	39.0	34.7	40.6	55.0	56.4
	Step 4	39.3	37.1	27.2	35.7	34.8	27.8	31.7	10.7	14.9
Stride length (cm)	Stride 1	66.7	74.9	73.5	82.0	70.8	81.4	87.5	74.7	69.1
	Stride 2	73.8	74.1	105.0	62.5	74.6	85.8	71.6	90.2	87.5
	Stride 3	72.9	79.3	75.3	62.7	73.8	62.6	72.3	65.7	71.3
Cadence (steps/min)	-	81.8	62.5	63.4	44.3	44.8	46.9	59.6	60.0	65.7
Stance duration (%)	-	60.9	69.4	58.0	54.3	60.2	65.4	65.8	68.5	64.9

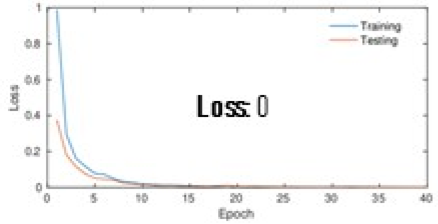
Biomechanics & Health monitoring

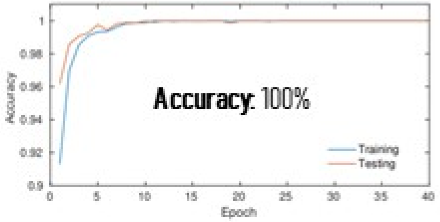
POF Smart Pants



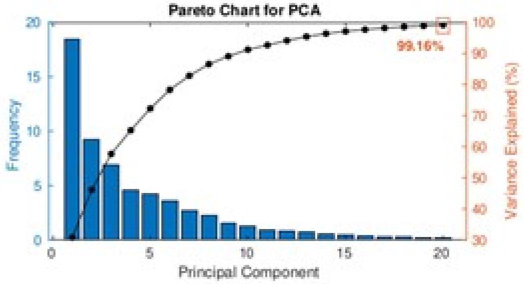
Human Activity Recognition Protocol (lower limbs)

FFNN Classification (neural network)

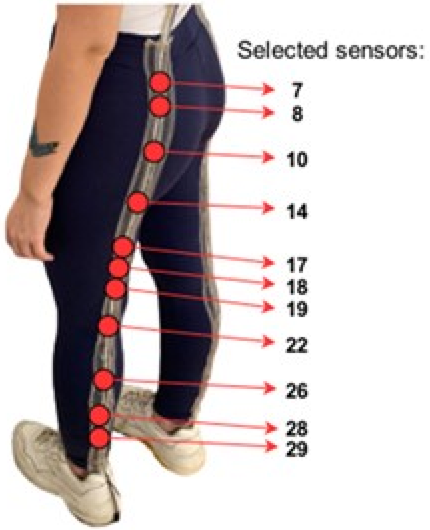




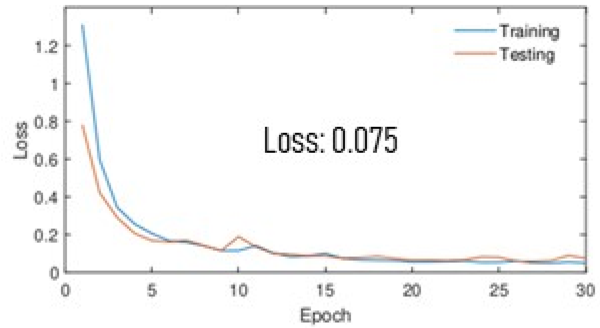
PCA: data dimensionality reduction

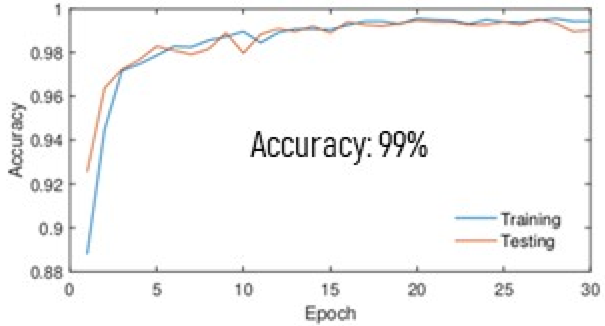


22 sensors (11 sensors/leg)

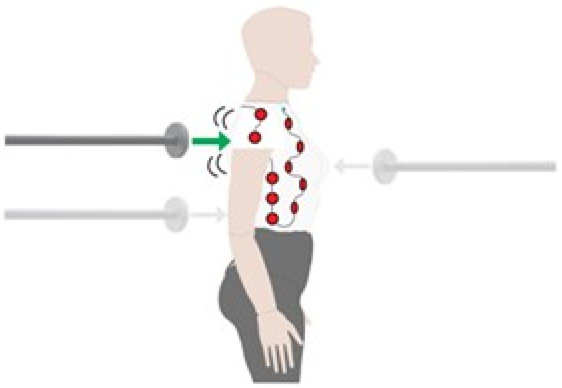


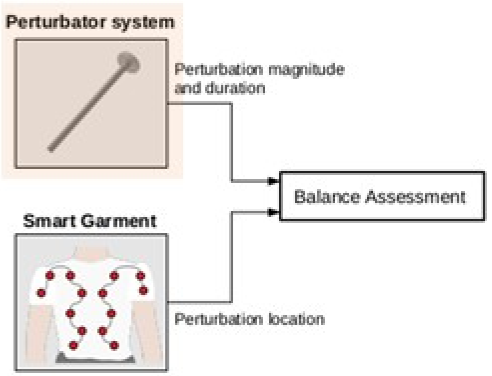
FFNN classification metrics: optimized structure

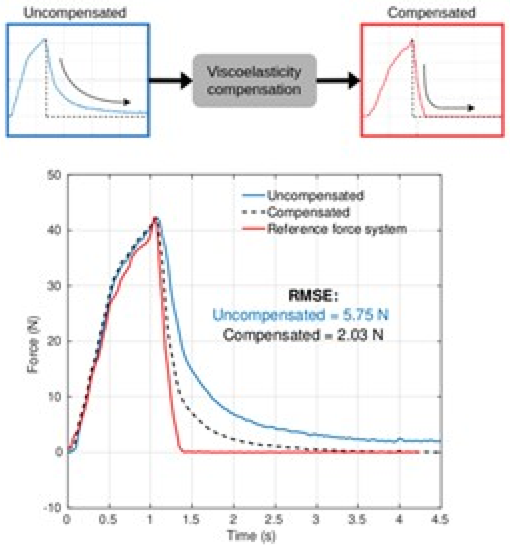




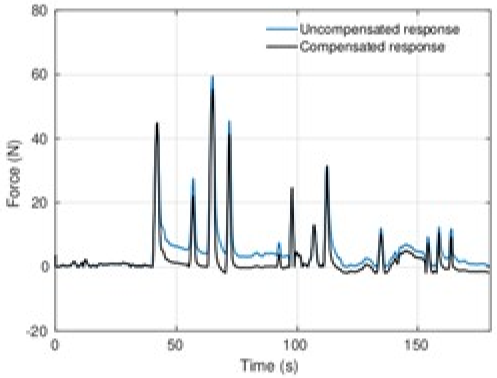
Balance Assessment Protocol

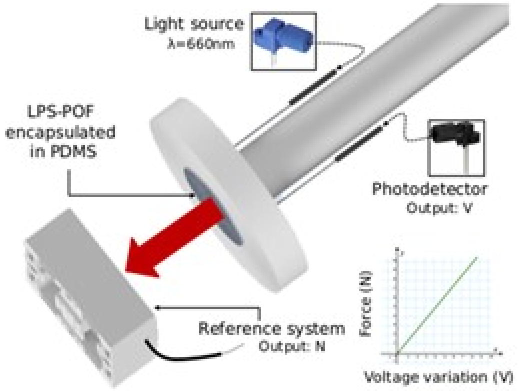


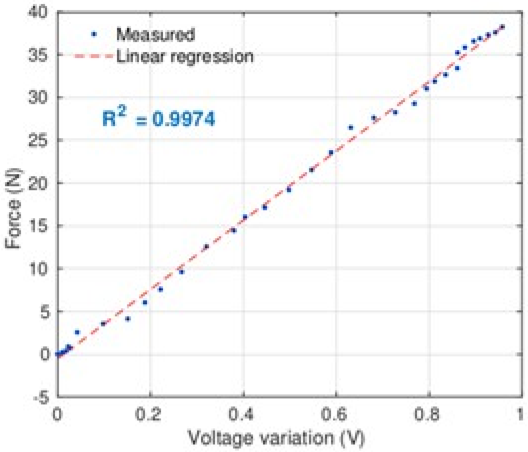




Perturbation during gait



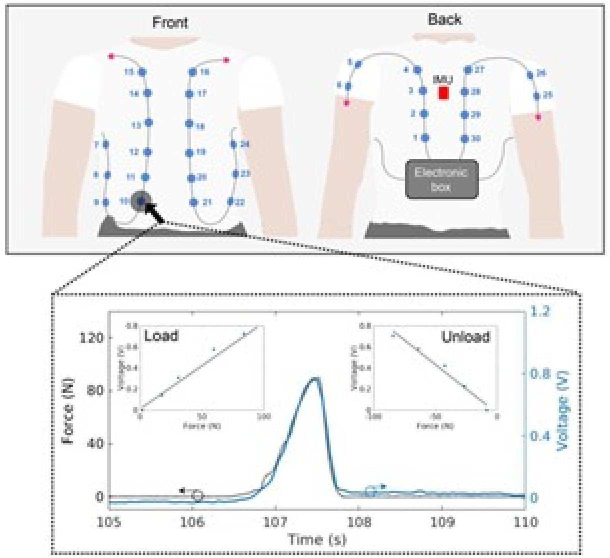


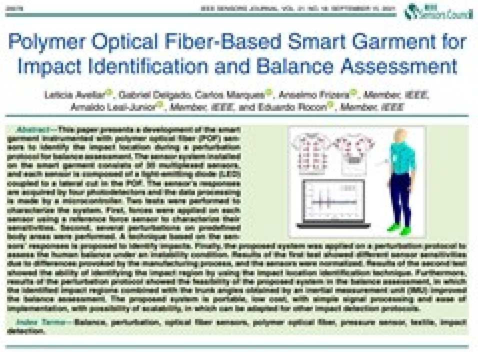


AVELLAR, L. ; DELGADO, G. ; ROCON, E. ; MARQUES, C.; FRIZERA, A. ; LEAL-JUNIOR, A. Polymer optical fiber-embedded force sensor system for assistive devices with dynamic compensation. IEEE Sensors Journal, v. 21, p. 13255-13262, 2021.

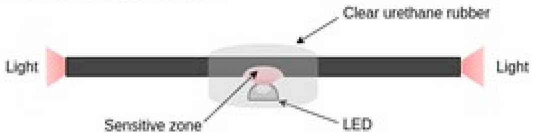
Balance Assessment Protocol

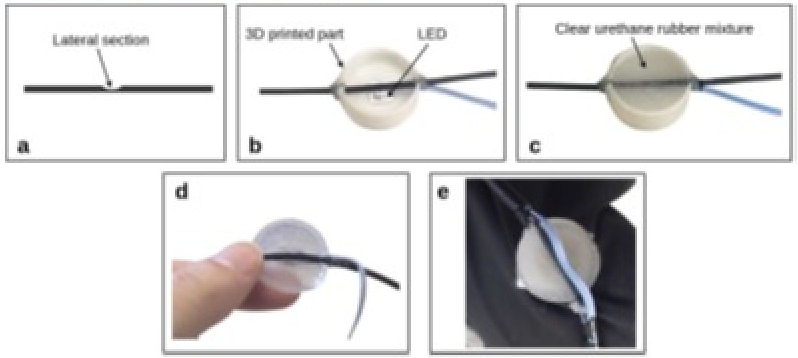
Smart Garment



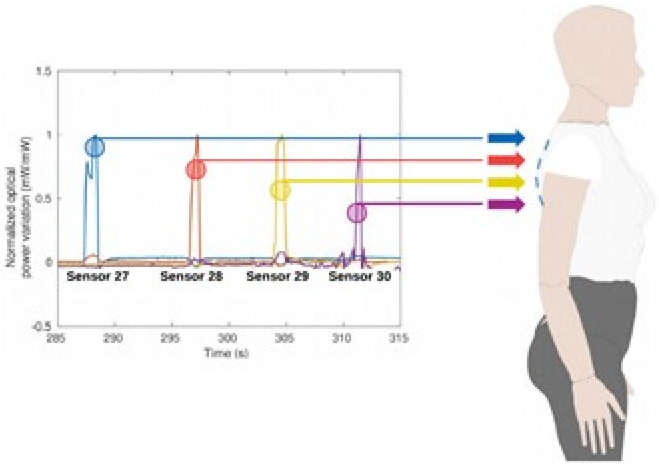

Polymer Optical Fiber-Based Smart Garment for Impact Identification and Balance Assessment

Sensors' fabrication





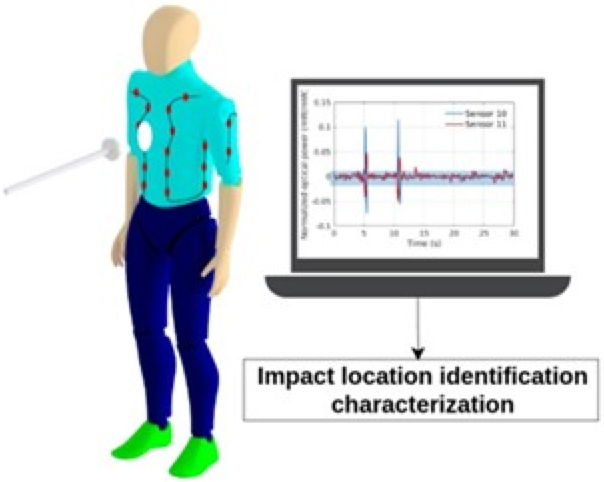
Force characterization

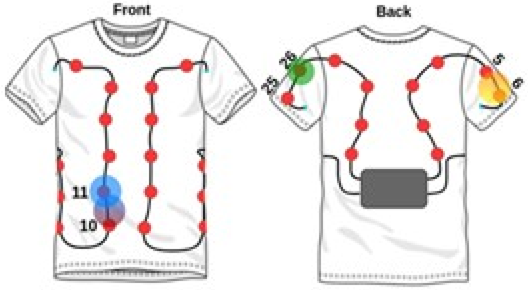


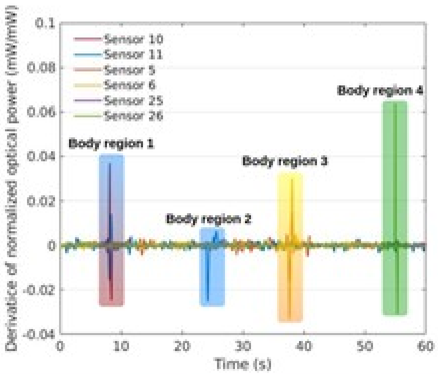
Sensor	Sensitivity (mV/N)	Sensor	Sensitivity (mV/N)
1	11.95	16	8.15
2	0.15	17	9.19
3	0.11	18	0.14
4	0.99	19	0.39
5	1.74	20	5.51
6	0.25	21	4.27
7	2.25	22	0.15
8	1.65	23	2.33
9	1.43	24	0.19
10	8.64	25	9.92
11	0.44	26	7.83
12	8.05	27	15.40
13	9.44	28	6.67
14	0.23	29	5.05
15	0.14	30	7.02

Balance Assessment Protocol

Identification of impact location





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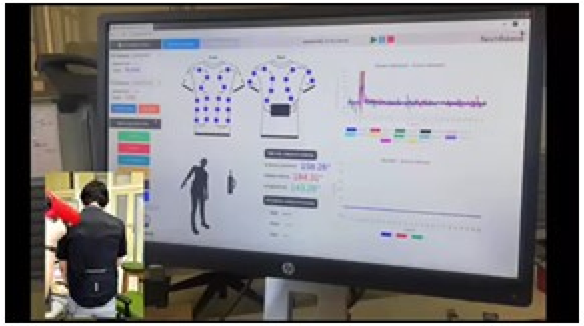
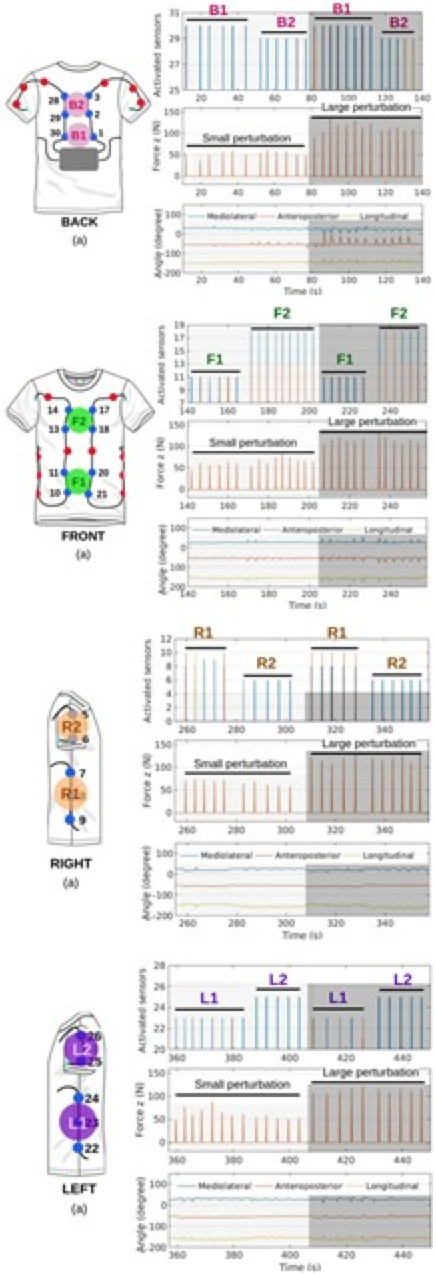
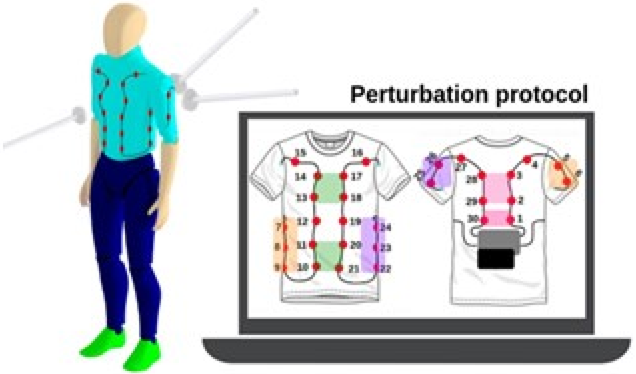
scientific reports

OPEN AI-enabled photonic smart garment for movement analysis

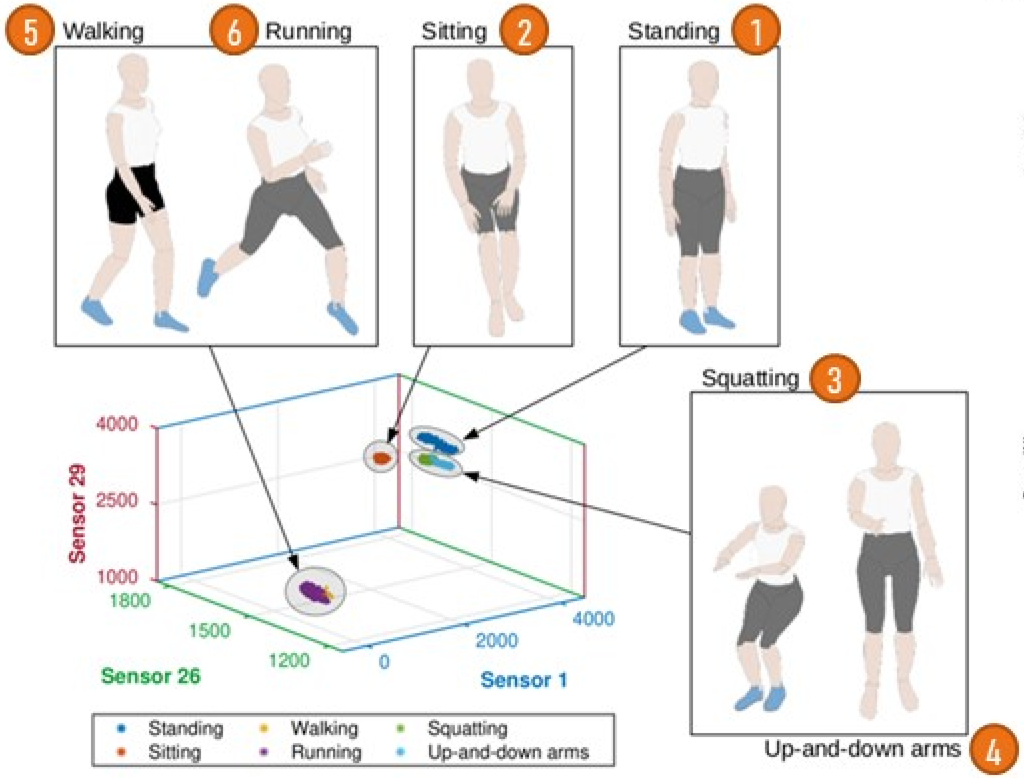




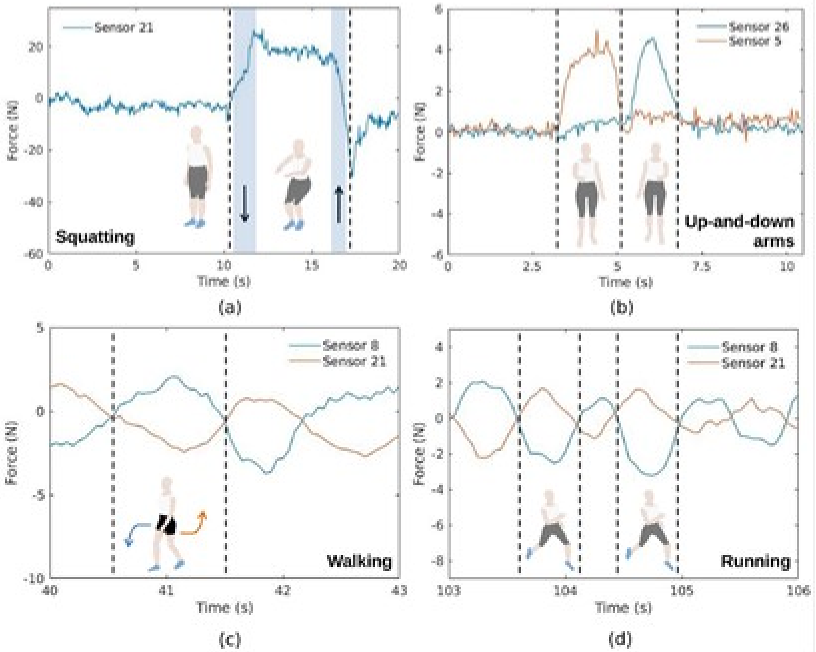


Biomechanics & Health Monitoring

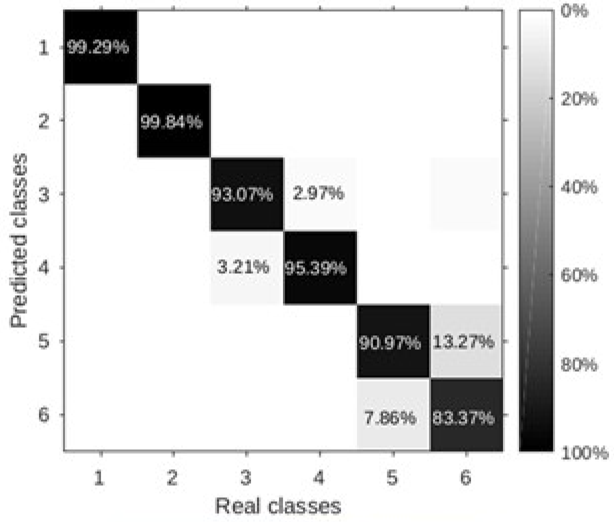
Smart Garment for Human Activity Recognition



Sensor Behaviour



kNN Classification

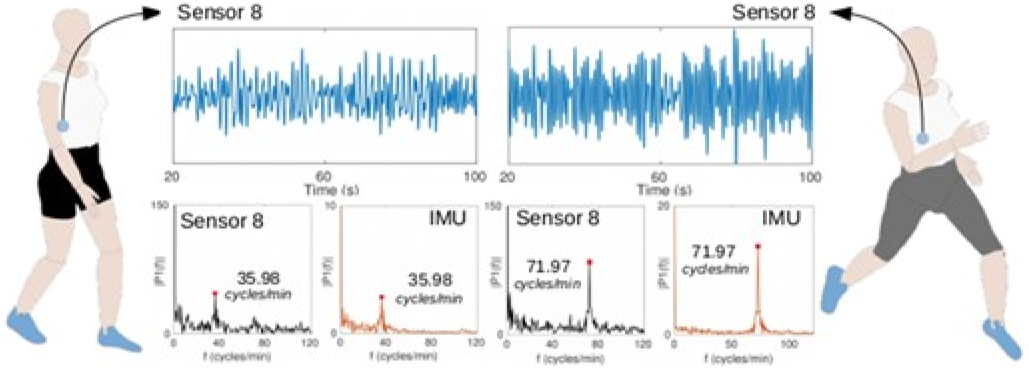


accuracy: 94.00 (0.14)%

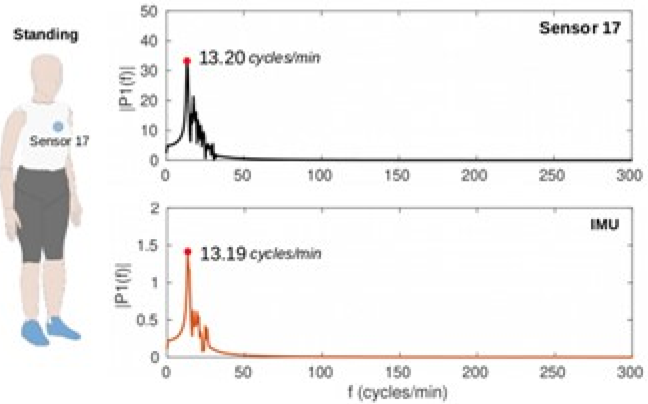
Biomechanics & Health Monitoring

Monitoring Gait and Breathing Rate with POF Smart Garment

Gait Cadence



Breathing rate



Movement-related parameters extraction

	Volunteer	Cadence (steps/min)		BR (cycles/min)
		Walking	Running	Standing
IMU	1	71.96	143.94	13.19
	2	79.14	155.92	13.79
	3	68.36	125.94	13.79
	4	73.16	146.34	14.39
POF Smart Garment	1	71.96	143.94	13.20
	2	77.38	156.54	13.9
	3	68.60	126.64	14.04
	4	72.12	145.98	14.6
Errors (%)	1	0	0	0.08
	2	2.22	0.40	0.80
	3	0.35	0.56	1.81
	4	1.42	0.27	1.46

Conclusions and final remarks

Soft Robots

current trends & future approaches

Biocompatible materials and bioinspired applications

By looking at nature:

- Soft animals are small or found in a medium that support their bodies
- Larger animals usually need a skeleton for bodyweight support

Merging rigid structures to soft robotics for assistive or rehabilitation devices

Simulation and control of soft robots

Power source technologies

- Solutions designed to specifically work with soft robots
- The human energy source to sustain wearable devices or prosthesis?

Polymer optical fiber (POF) sensors

- Alternative to electrical/ electronic sensors
- Higher flexibility
- Lower Young's modulus
- High elastic limits and impact resistance
- New/biocompatible materials
- Advanced interrogation techniques

Optical fiber sensors for the next generation of rehabilitation robotics

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