Benchmarking lower limb wearable robots: towards practical and evidence-based solutions

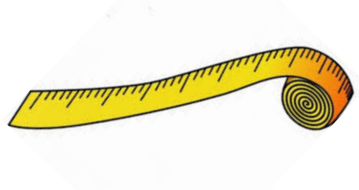
BALANCE H-R-H BioMot WALK-MAN KOROIBOT

What is a Benchmark?

"A standard or point of reference against which things may be compared or assessed"

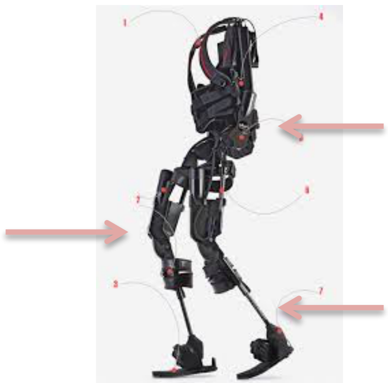
Benchmarking

1. To assess systems quantitatively and impartially



2. To compare different solutions

3. To demonstrate that they can work out of the lab



4. To identify critical issues and improve the system

Why Benchmarking?

From Idea to the market →

Technology readiness levels (TRLs)

1 2 3 4 5 6 7 8 9

Discovery/ Concept De… tion

Laboratory Validation

Ope… ater Val… ion

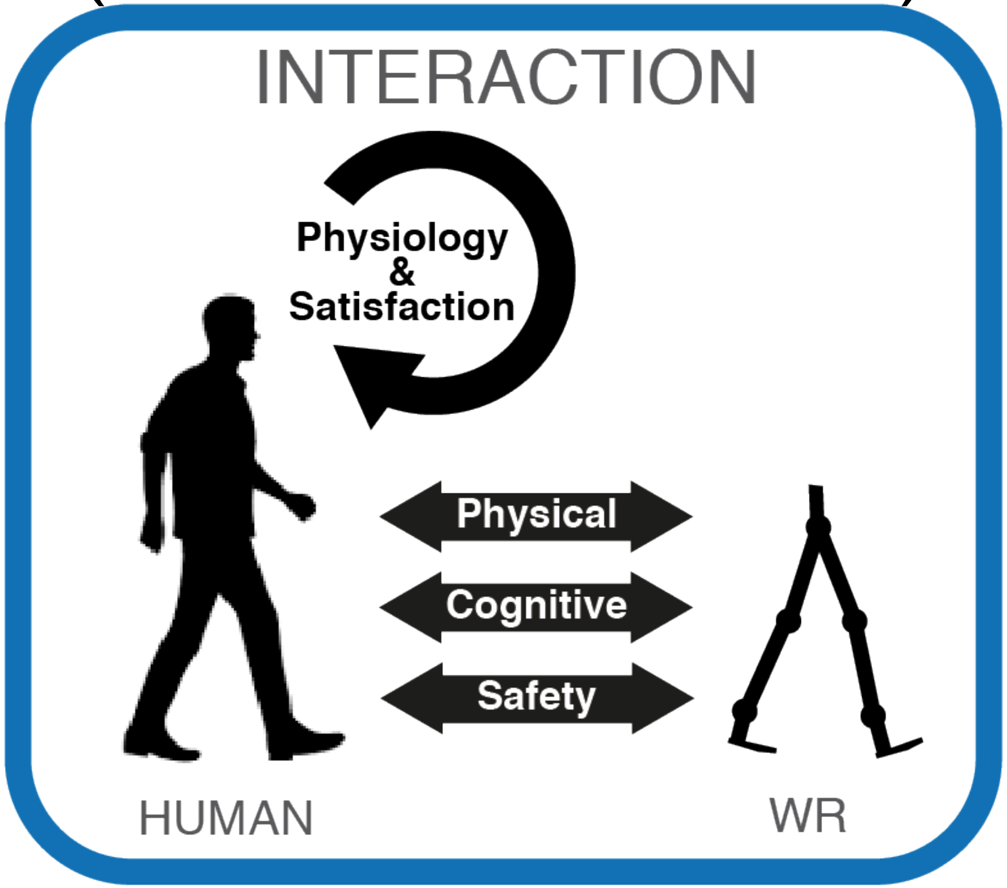
Commercial Deployment

…emo & …ation

We need BENCHMARKS

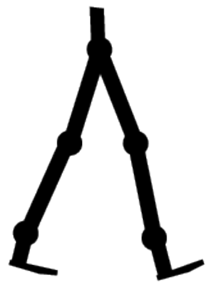
WHAT TO BENCHMARK?

(WEARABLE ROBOTICS)



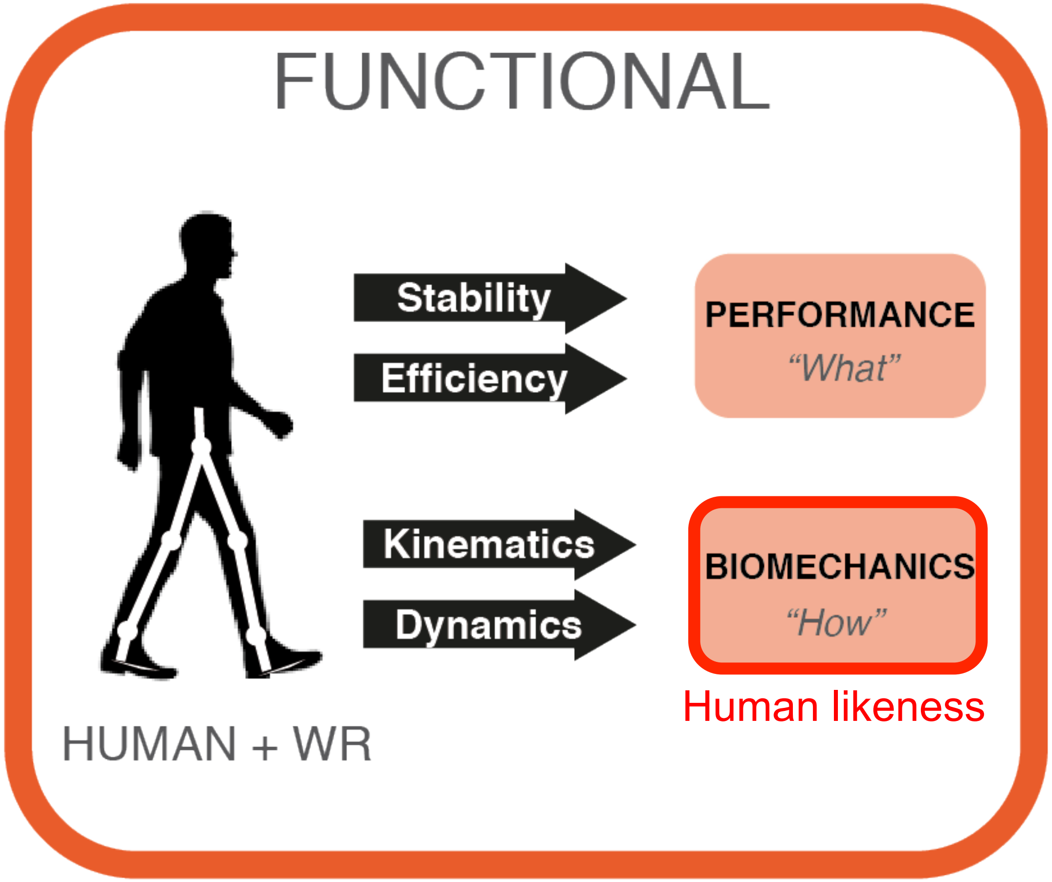
What to Benchmark?

HUMAN + WR



WR

What to Benchmark?



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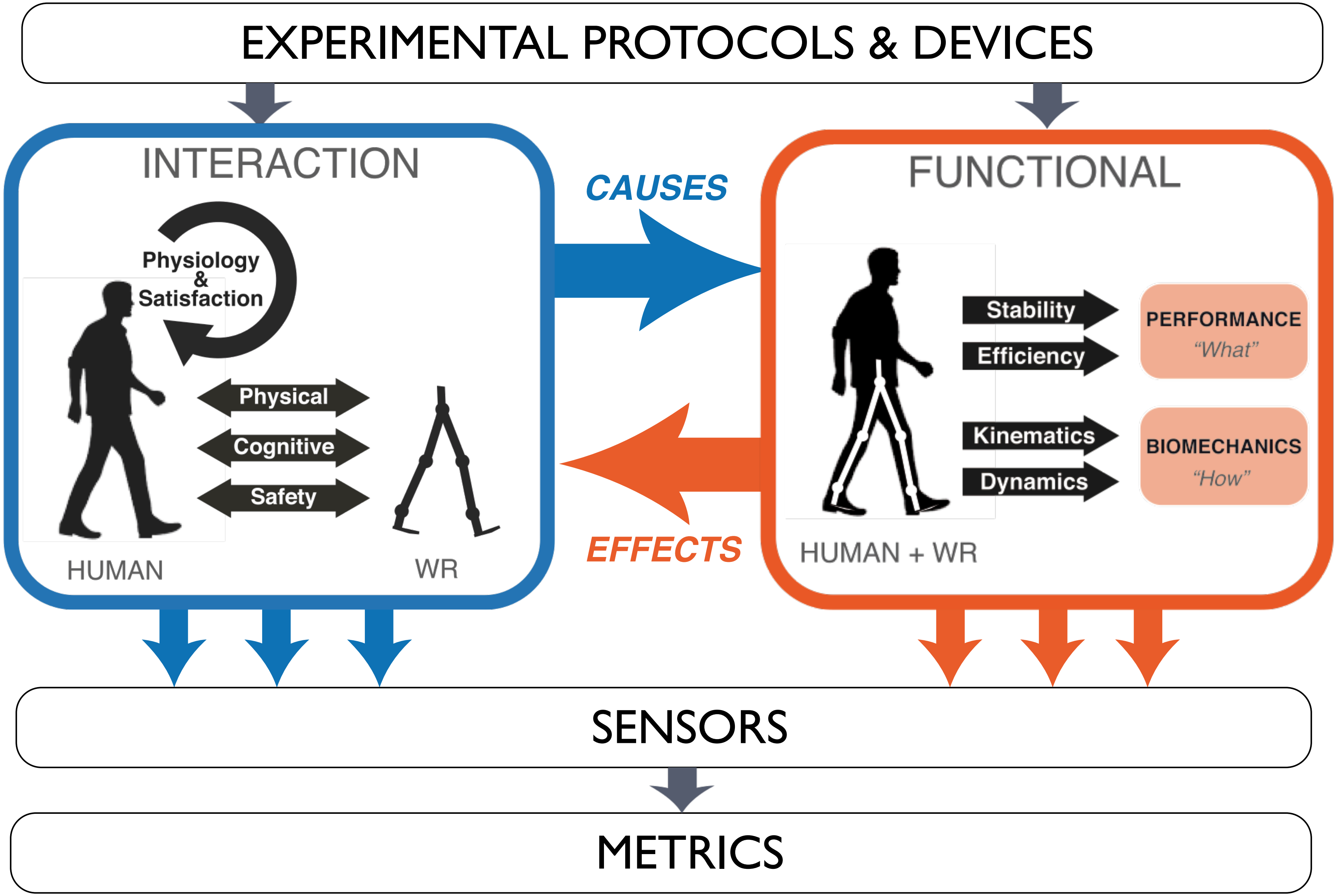
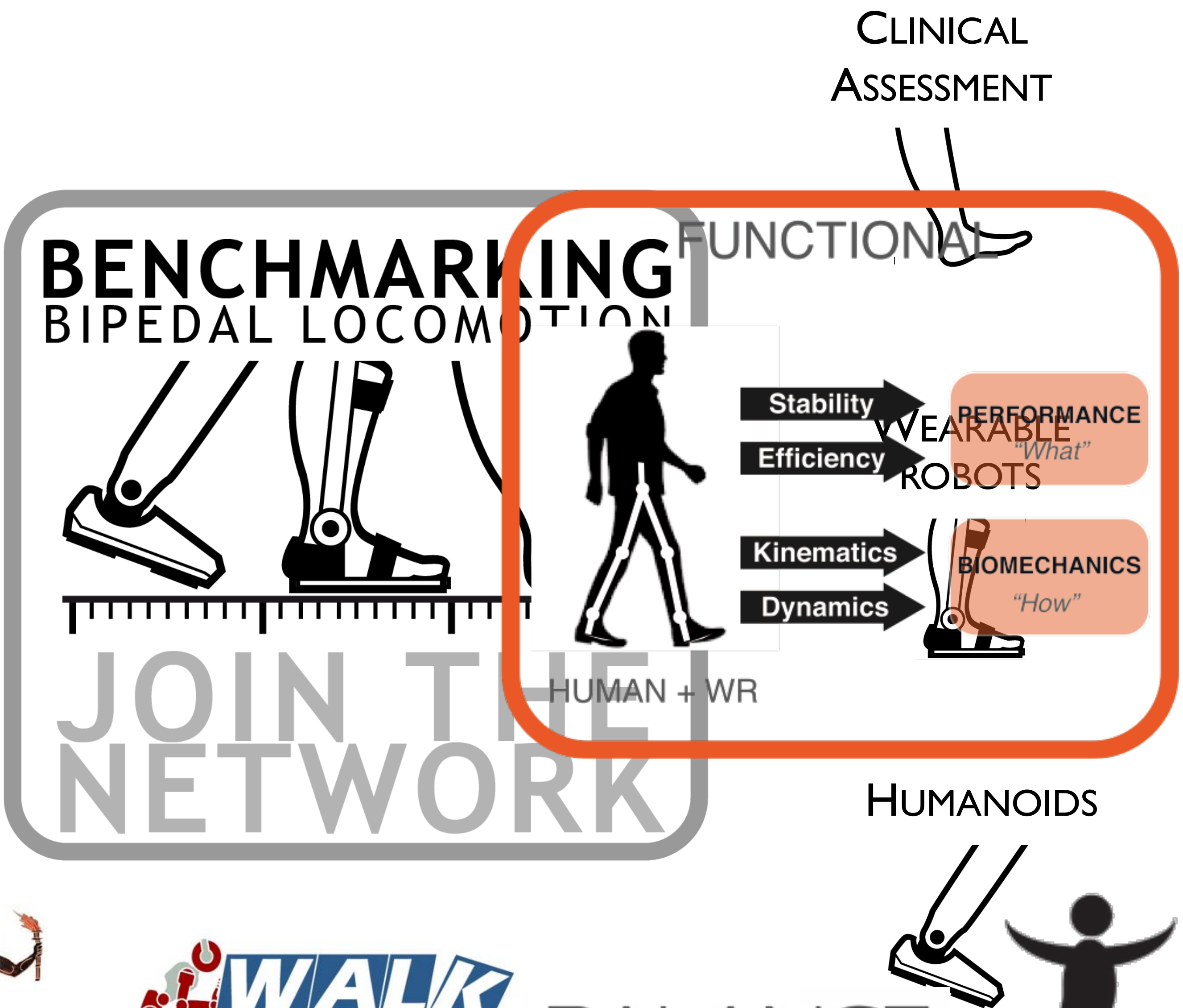
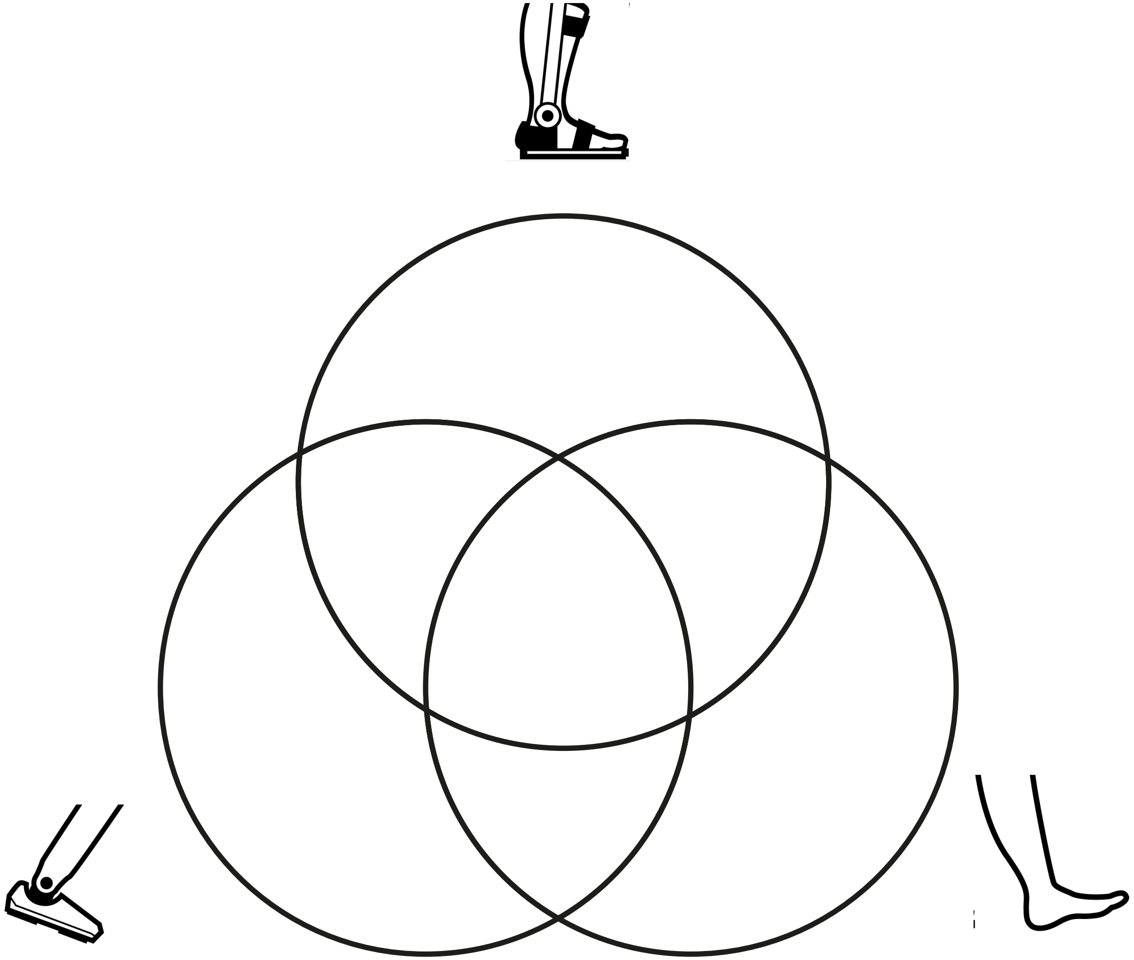
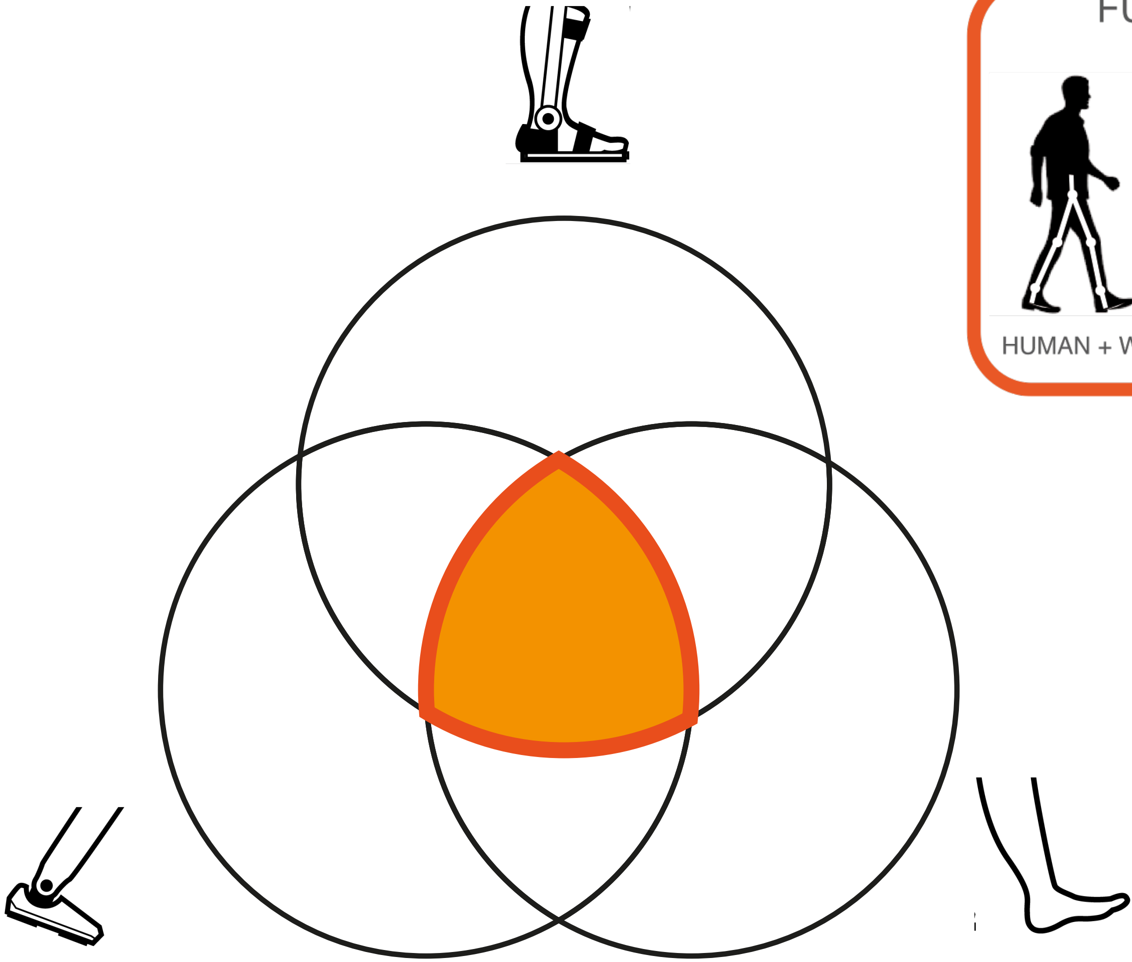
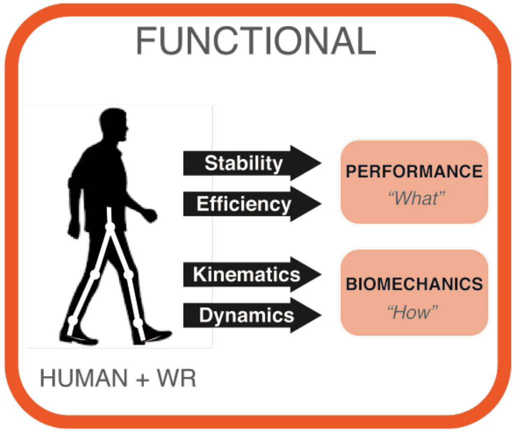


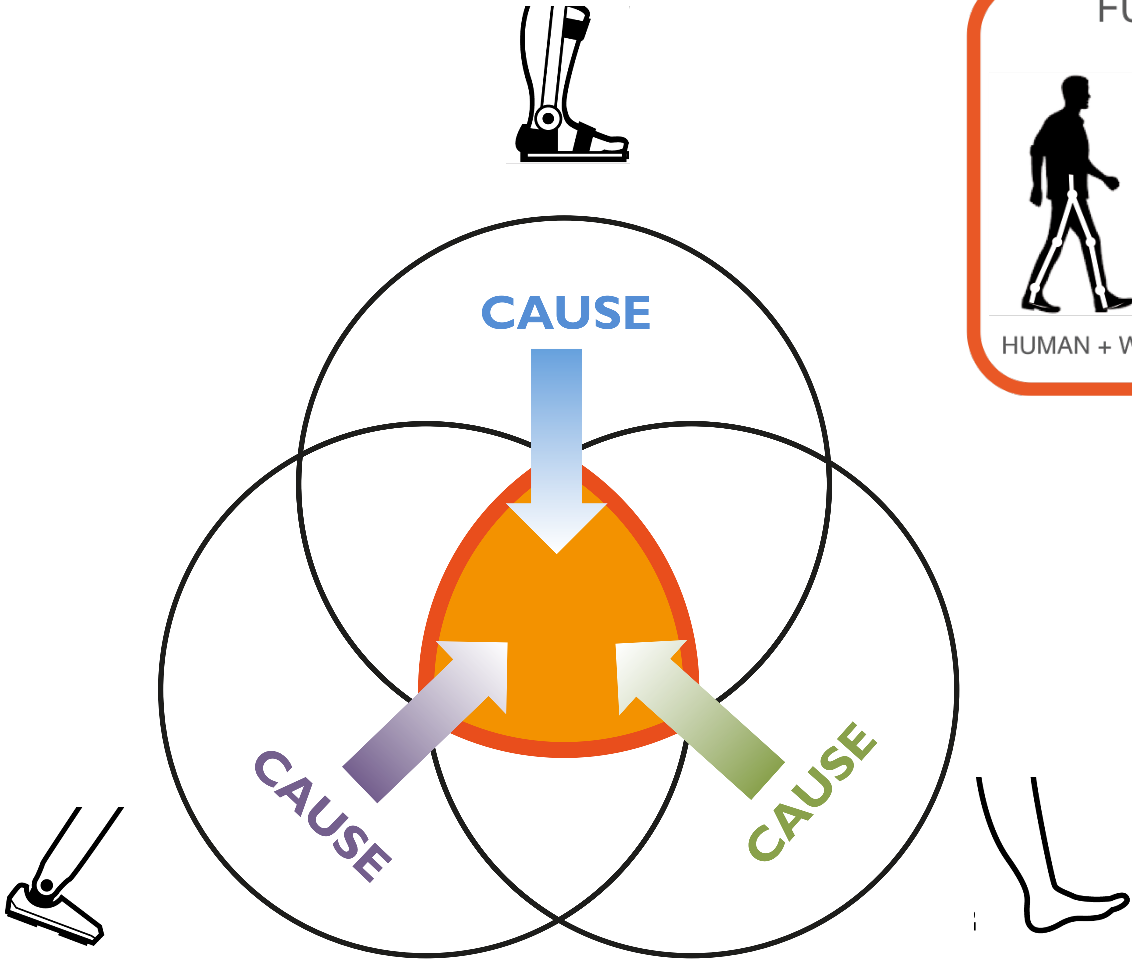
FUNCTIONAL BENCHMARKS








FUNCTIONAL
Stability
Efficiency
Kinematics
Dynamics
PERFORMANCE
"What"
BIOMECHANICS
"How"
HUMAN + WR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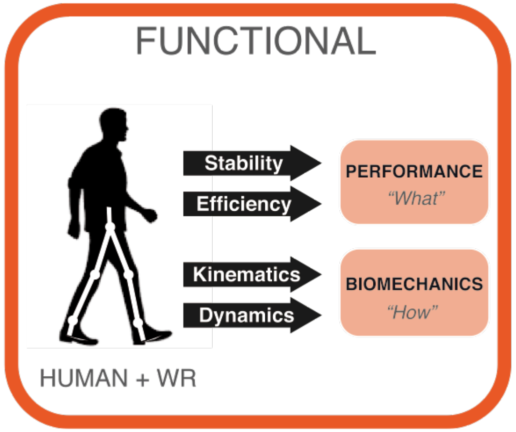
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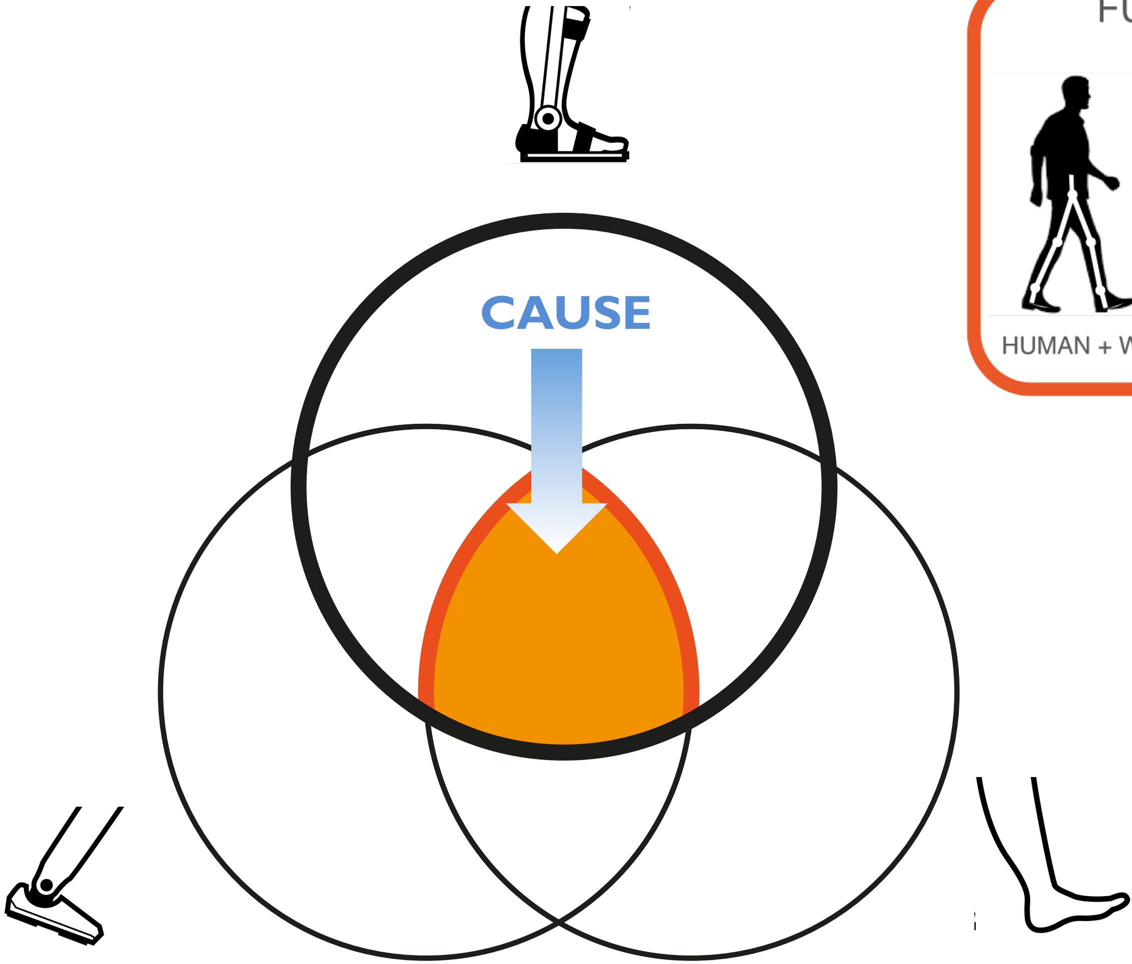
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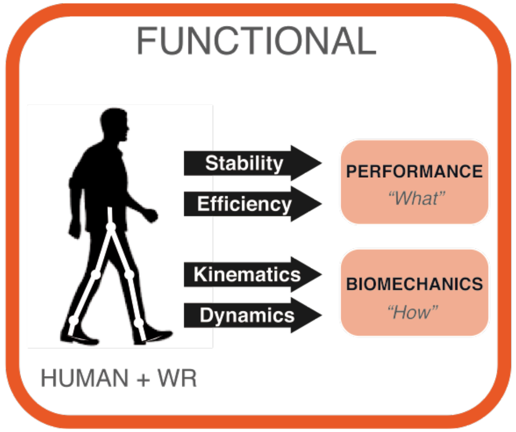
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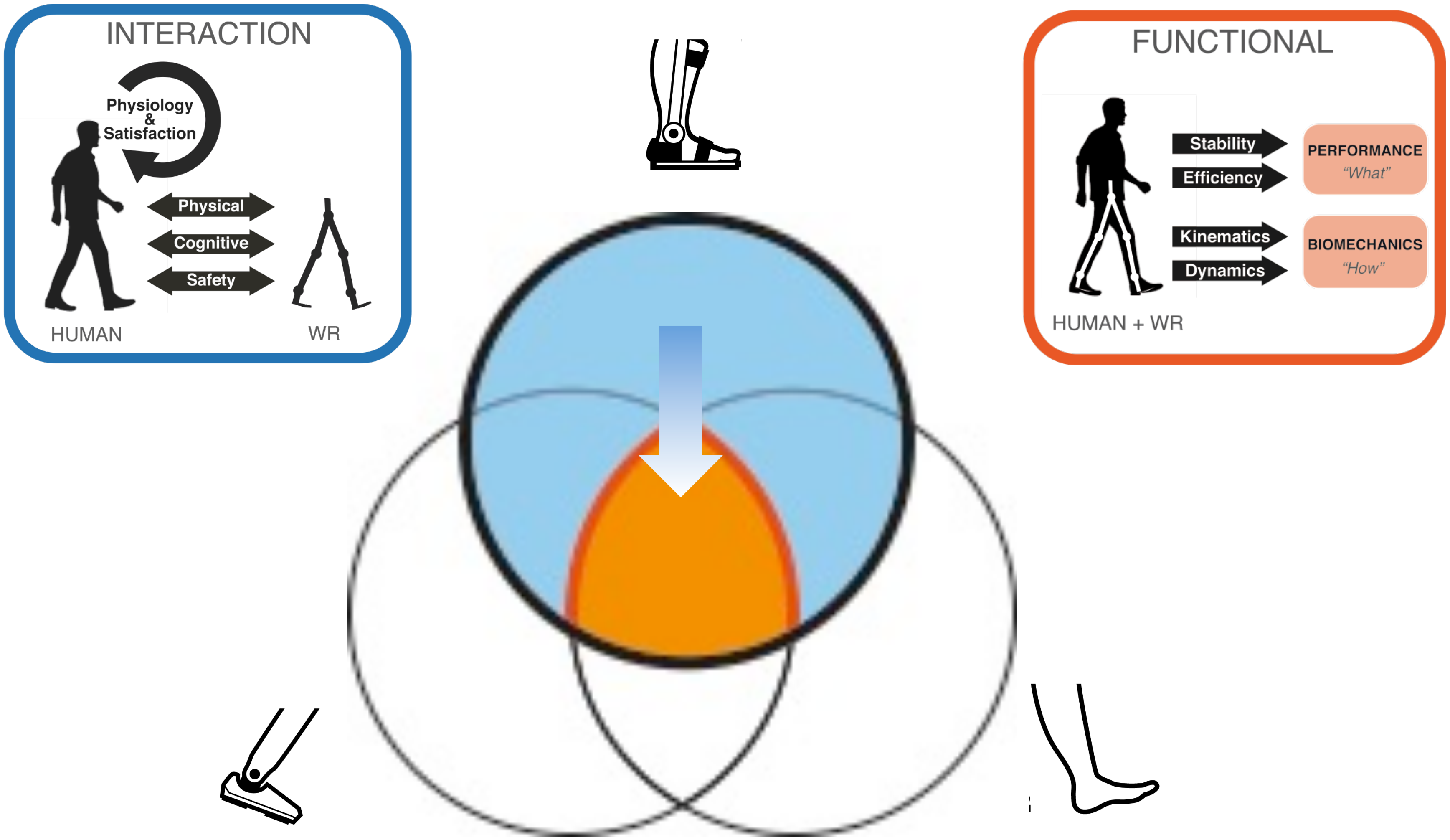
INTERACTION
Physiology
&
Satisfaction
Physical
Cognitive
Safety
HUMAN
WR
FUNCTIONAL
Stability
Efficiency
Kinematics
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PERFORMANCE
"What"
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"How"
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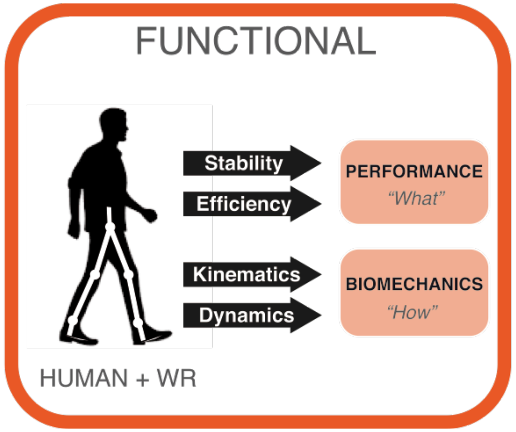
COMMUNITY-BASED APPROACH

COLLABORATIVE EFFORTS:

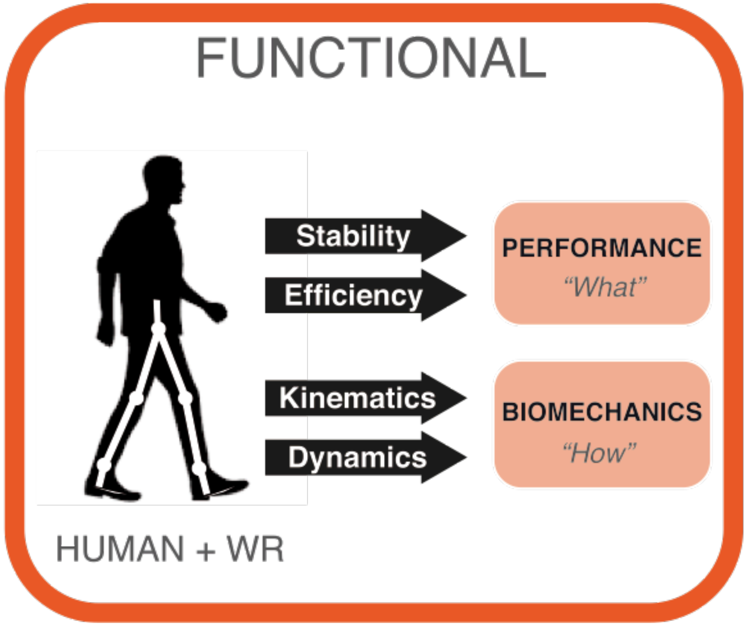
- 2013 IEEE-RAS International Conference on Humanoid Robots, Workshop on "Benchmarking of human-like robotic locomotion"
- 2013 Mailing list on "benchmarking bipedal locomotion" https://listas.csic.es/wws/info/benchmarking_list)
- 2014 Web-based survey. Still accessible at: http://goo.gl/forms/FL9Pd1xXgb
- 2014 International workshop on wearable robots (www.werob2014.org), Session on "Benchmarking, Regulatory and funding aspects of WRs"
- 2014 IEEE-RAS International Conference on Humanoid Robots, Workshop on "Benchmarking of bipedal locomotion"
- 2015 European Robotics Forum, Session on "Replicable robotics research and benchmarking"



Taxonomy for Motor Skills

ENVIRONMENT		FUNCTION: BODY POSTURE	FUNCTION: BODY TRANSPORT
STATIONARY	INTERTRIAL VARIABILITY: NO	*Static horizontal surface*	*Horizontal ground at constant speed*
STATIONARY	INTERTRIAL VARIABILITY: NO	*Static inclined surface*	*Sloped ground*
STATIONARY	INTERTRIAL VARIABILITY: YES	*Different static surfaces*	*Horizontal ground at variable speed (including start-stop)*
STATIONARY	INTERTRIAL VARIABILITY: YES		*Variable slopes*
STATIONARY	INTERTRIAL VARIABILITY: YES		*Irregular terrain*
IN MOTION	INTERTRIAL VARIABILITY: NO	*Sinusoidal surface tilts*	*Treadmill at constant speed*
IN MOTION	INTERTRIAL VARIABILITY: NO	*Sinusoidal surface translations*	*Soft terrain with constant compliance*
IN MOTION	INTERTRIAL VARIABILITY: NO	*Bearing constant weight*	*Bearing constant weight*
IN MOTION	INTERTRIAL VARIABILITY: YES	*Pushes*	*Pushes*
IN MOTION	INTERTRIAL VARIABILITY: YES	*Sudden or pseudorandom surface tilts*	*Treadmill at variable speed (including start-stop)*
IN MOTION	INTERTRIAL VARIABILITY: YES	*Sudden surface translations*	*Seesaw*
IN MOTION	INTERTRIAL VARIABILITY: YES	*Body sway referenced platform (BSRP)*	*Soft ground with variable compliance*

Unified Scheme*:

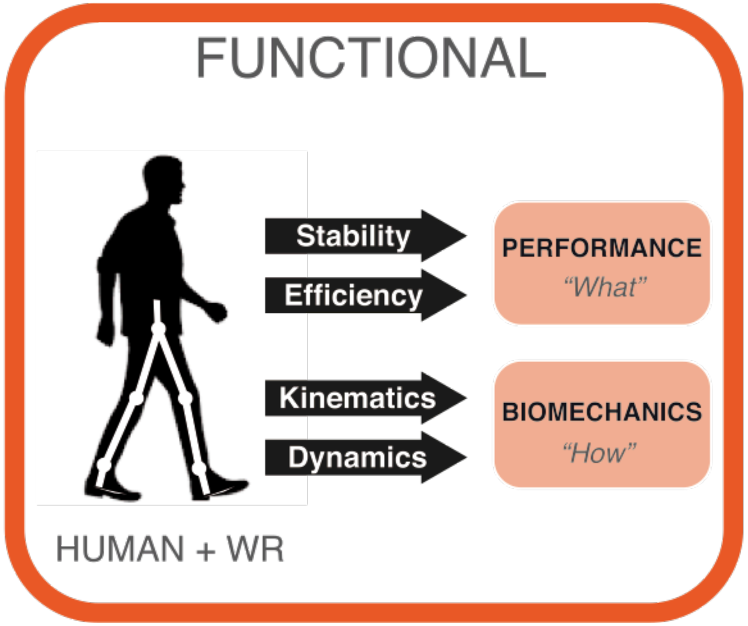


**Torricelli et al. Benchmarking bipedal locomotion in humanoids, wearable robots and humans: a unified scheme. IEEE Robotics and Automation Magazine (in press)*

BENCHMARKS

		NAME	DESCRIPTION	BENCHMARK
PERFORMANCE	STABILITY	Robustness (Intra-trial stability)	Ability to cope with known motor skill without falling.	Time until falling
				Cycles until falling
		Versatility (Inter-trial stability)	Ability to cope with changing scenario without falling	Success rate across N different trials
		Gross body equilibrium	Ability to maintain upright posture	Energy stability margin (ESM [7])
	EFFICIENCY	Global energy consumption	Ability to transport body with low energetic costs	Specific energetic cost of transport C_{et}
				Specific mechanical cost of transport C_{mt}
		Passivity	Ability to minimize joint torques during walking	Passive Gait Measure [8]
HUMAN LIKENESS	KINEMATICS	Gross body motion	Motion of the whole body expressed by global variables	CoM trajectory (correlation, dynamic time warping [9])
				Harmony [10]
				Body sway (Frequency Response Function, [12])
				Natural looking motion [13]
		Single joint motion	Motion of the single joints or limbs taken separately	Joint trajectory (correlation, dynamic time warping [9])
				Knee, ankle forefoot rocker [16]
		Intra-limb coordination	Ability to move multiple joints coordinately	Kinematic synergies (REF)
		Inter-limb coordination	Ability to move symmetrically	Ratio Index [14]
	DYNAMICS	Gross body kinetics	Forces exerted between the whole body and the environment	Ground reaction forces (correlation, dynamic time warping [9])
		Single joint kinetics	Force exerted among limbs	Joint torques (correlation, dynamic time warping [9])
		Dynamic similarity	Ability of having leg pattern dynamically similar to most locomoting animals.	Froude number (Dimensionless gait velocity) [17]
		Dynamicity	Ability to use falling state for body progression	Dynamic Gait Measure [8]
		External compliance	Ability to respond resiliently to external disturbances	Impulse Response Function [12]
		Internal compliance	Ability to store and release energy	Active/net joint torque (REF)
		Reaction time	Ability to give a fast motor response to the disturbance when it appears.	Time from disturbance and initiation of motor action

Unified Scheme*:



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PROTOCOL DEFINITIONS

MOTOR SKILL

QUALITATIVE

Name of the skill:……………………………..

Function:
- ☐ Body posture
- ☐ Body transport

Environment:
- ☐ Stationary
- ☐ In motion

Intertrial variability:
- ☐ Yes
- ☐ No

Type of support:
- ☐ Static surface
- ☐ Moving surface
- ☐ Irregular terrain (rigid, soft, obstacles)
- ☐ Other ………………………

Type of disturbance:
- ☐ Unperturbed
- ☐ Slopes
- ☐ Tilting surface
- ☐ Translating surface
- ☐ Added weight
- ☐ External pushes
- ☐ Other ………………………

QUANTITATIVE

Direction of disturbance:
- ☐ Sagittal plane
- ☐ Frontal plane
- ☐ Other ………………………

Location of disturbance:
- ☐ Foot (exact location:………………………)
- ☐ Leg (exact location:………………………)
- ☐ Trunk (exact location:………………………)
- ☐ Arms (exact location:………………………)
- ☐ Other ………………………

Magnitude of disturbance:
- Starting value: ………………………
- Incremental value:……………………

Frequency of disturbance:
- Starting value (cycle/min): …………………
- Incremental value:……………………

Cycle waveform:
- ☐ Impulsive
- ☐ Continuous (specify:……………….)

Duration of the trial:
- ☐ Number of cycles: ……………
- ☐ Time: ……………
- ☐ Distance: ……………

Duration of the experiment:
- Number of trials: ……………

EXPERIMENTAL PROTOCOL

PROCEDURE

1) Set the measurement system according to the required outcome variables (see section MEASURES)
2) Set magnitude and frequency of disturbance
3) Put bipedal system in initial position
4) Start recording
5) Start trial
6) Stop trial
7) Stop recording
8) Store recorded data
9) Repeat steps 3 to 8 until the defined number of trials
10) Change the condition according to magnitude and frequency ranges
11) Repeat from steps 2 to 11 until the biped/person falls
12) Analyze the data according to the selected benchmarks (see BENCHMARKS)
13) Present the data according to the method (see RESULTS)

MEASURES

Outcome variables:
- ☐ Duration of cycles, trials and experiment
- ☐ Nº of cycles performed
- ☐ Nº of trials performed
- ☐ Joint angles (time course)
- ☐ Ground reaction forces (time course)
- ☐ CoP trajectory (time course)
- ☐ CoM trajectory (time course)
- ☐ Detection of falling events (time)
- ☐ Applied disturbance (time course)
- ☐ Other ………………………

BENCHMARKS

PERFORMANCE:

Stability
- ☐ Intra-trial stability
- ☐ Inter-trial stability
- ☐ Gross body equilibrium

Efficiency
- ☐ Global energy consumpt.
- ☐ Passivity
- ☐ Reaction time

HUMAN LIKENESS:

Kinematics
- ☐ Gross body motion
- ☐ Joint motion
- ☐ Intra-limb coordination
- ☐ Inter-limb coordination

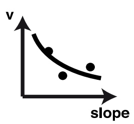
Dynamics
- ☐ Gross body kinetics
- ☐ Joint kinetics
- ☐ Dynamic similarity
- ☐ Dynamicity
- ☐ External compliance
- ☐ Internal compliance

RESULTS

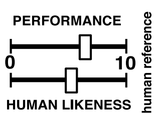
☐ Numerical

	10°	15°	20°
1	6.34	5.41	3.23
2	3.80	3.23	2.18
3	3.14	3.02	2.20
4	2.96	2.45	1.34

☐ Graphical



☐ Score



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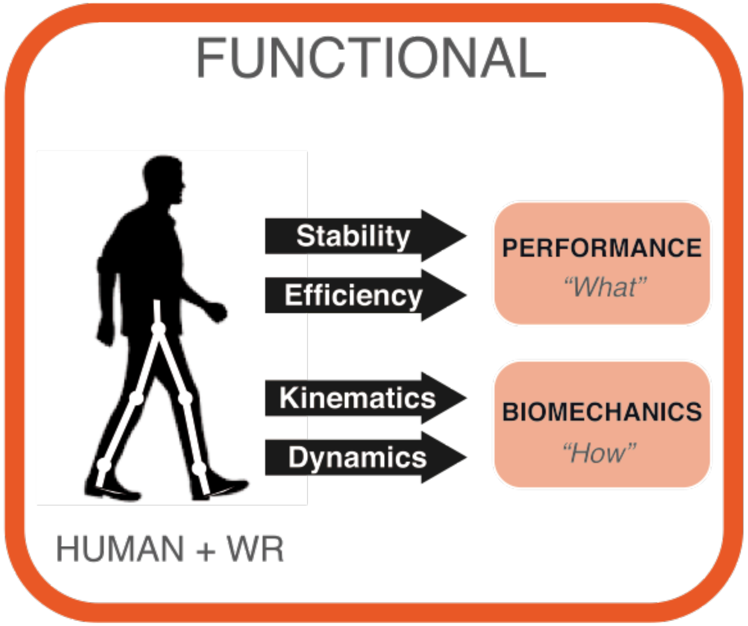

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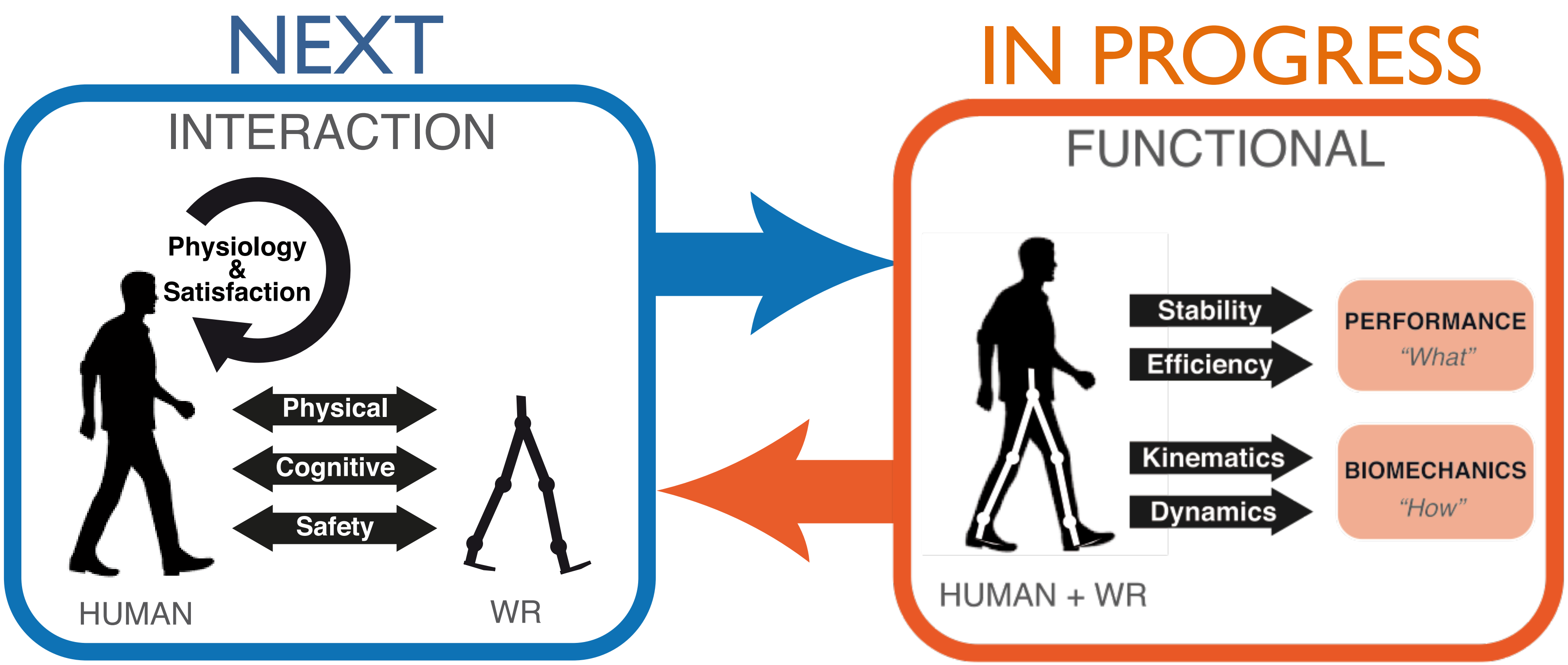
CONCLUSION



- Defining experimental protocols
- Elaborating new metrics (benchmarks)
- Proposing easy-to-use sensors

SHARABLE ACROSS LABS!

www.benchmarkinglocomotion.org