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Analyzing the role of arm support during robot-assisted leg movements

By Florian L. Haufe, Roushanak H. Hassani, Robert Riener and Peter Wolf

To complement the assistance of a wearable robot, users with a leg weakness often rely on balance and body-weight support through their arms and passive walking aids. A precise quantification of this arm support is crucial to better understand the real-world robot dynamics, the human-robot interaction, and the human user performance.

In this article, we present a novel measurement system, the InSight Crutches, that allows such a quantification, and evaluate the crutches' functionality in three exemplary movement scenarios with different wearable robots and users with spinal cord injury.

A Wearable Robotics Perspective on Arm Support

Arm Support during Robot-Assisted Movements

Most wearable robots for movement augmentation, assistance or training of the legs are not fully self-balancing (e.g. [1-3]). Those robots also require user contributions to weight-bearing or leg advancement during parts of the movements.

In industrial, recreational or military settings, unimpaired users can readily assist balance and contribute to weight-bearing and leg advancement through their legs. These user contributions allow for robotic devices that have fewer actuated degrees of freedom and require less powerful motors. As an effect, robotic devices can be lighter and less obtrusive. Such wearable robots can potentially better adapt to real-world scenarios than their fully actuated counterparts because they are able to seamlessly change from active assistance to "transparent" behavior with maximal freedom of movement for the user [4].

Wearable robots that are designed for users with neuromuscular impairments such as spinal cord injury, stroke, multiple sclerosis, or muscle dystrophy cannot rely on similar user contributions. Here, another means of achieving stable movements is required. In a few exoskeletons (e.g. [5, 6]), this challenge has been addressed by increasing the active balancing capabilities of the robots to an extent that allows for statically stable gait. Here, we define "static stability" as stability during movements in which the projection of the center of mass to the ground is always within the base of support [7]. The usability of these exoskeletons remains limited due to their very large mass and relatively slow movement speed that is dictated by limited step length and cadence. Instead, the more common choice is to additionally utilize passive mobility aids for the arms such as crutches.

Crutches allow users with a leg weakness to increase their base of support. Thereby, they can independently maintain static stability while wearing a robot for leg assistance. Importantly, the use of crutches creates two additional kinematic chains through which the user interacts with the environment in parallel to the legs (see Figure 1). In an analysis of the overall interaction between the human user wearing a robot and the environment, the support through the arms and the crutches need to be separately quantified.

Rationale for the Analysis of Arm Support

The analysis of the interaction between the human user wearing a robot and the environment is of central interest in evaluations ranging from technical benchmarking of robotic systems, over the analysis of the physical human-robot interaction, to user performance assessments.

Defining standardized benchmarks has been a key objective in the field of wearable robotics in recent years. While the specifics of such benchmarks are still being discussed, it is evident that compensatory efforts from the user – e.g. with the arms and crutches – need to be captured and accounted for.

Similarly, the analysis of physical human-robot interaction can be facilitated by model-based approaches which are typically driven by measurements of external interaction forces. Internal measurements directly at the interface between the wearable robot and the user are often challenging to implement and might sometimes even alter the interaction dynamics. Information about the external interaction through the crutches can help to circumvent such measurements, even during parallel support through the legs and the crutches.

Further, for user performance assessments, the interaction through the crutches can be a direct indicator of balance skills or compensatory efforts related to gait asymmetry. The information about the total crutch load can help to adjust the level of robotic assistance in a way that avoids nerve [8] or tendon [9] damage in the arms over prolonged use.

All these evaluations crucially depend on the separate quantification of how much the user contributes to movements through the crutches, and how much assistance is provided by the wearable robot. Such a quantification is only possible by using “instrumented crutches” that can measure crutch forces for an analysis of interaction dynamics. Consequently, instrumented crutches are an essential tool in wearable robotics research and development, and in the real-world evaluation of wearable robots.

In previous work [10, 11], commercially available 6-axis strain gauge load cells (e.g. [12]) have been adapted for crutch force measurements at up to 1200 Hz with an accuracy of about 2 %. However, these research-focused assemblies were relatively heavy (each sensor alone 600 g [12]) and tethered to external amplifiers and thereby inherently limited to lab settings. Other proposed devices (e.g. [13, 14]) allowed for untethered operation and wireless communication, and were more lightweight (crutch in total 720 g [14]). Yet, these devices were primarily directed towards therapeutic use, and only measured uniaxial forces at much lower sampling frequencies of 10 Hz [13] to 80 Hz [14]. Recent devices [15] that have aimed to combine the sensory performance of research devices and the flexible use of therapeutic devices were based on custom assemblies which seem hard to repeatedly manufacture consistently, might not be sufficiently robust for real-world testing, and have not been thoroughly validated.

In this article, we revisit the requirements for an instrumented crutch system that can be used in conjunction with wearable robots during both real-world evaluations and biomechanical analyses. Based thereon, we describe the design and functionality of the InSight Crutches, a novel system to analyze arm support during robot-assisted movements. In addition, we present a case study series in which the InSight Crutches are used to analyze the effect of state-of-the-art robotic systems on the arm contributions of users with incomplete spinal cord injury during exemplary movement scenarios (see Figure 2).

Requirements for an Instrumented Crutch System

The diversity of scenarios in which wearable robots are used today leads to a comprehensive set of practical and technical requirements for an instrumented crutch system (see Table 1).

For use in benchmarking, crutch force measurements need to be easily reproducible with validated sensor technology. The sensor setup should not require any user assembly or individual calibration that might prove detrimental to the overall comparability of measurements. This requirement favors using commercially available sensors that come pre-calibrated from the vendor and are available worldwide.

To determine the required number of measured axes for the sensor, we modelled the contact interfaces of the human user to the crutch as a joint bearing (three reaction forces, three degrees of freedom, DOF) at the crutch handle and as a support bearing (two reaction forces, four DOF) at the crutch cuff (see Figure 3). The interface of the crutch tip to the ground was modelled as a joint bearing (three reaction forces, three DOF). This modelling approach resulted in a total of eight unknown reaction forces $\left\{C_{1,2}, H_{1-3}, T_{1-3}\right\}$ and a known gravitational force G acting on the crutch. The associated analysis of impulse and angular momentum revealed that not all the six equations of motion are independent, such that only five out of eight unknowns could be eliminated through calculations. Accordingly, three more contact force measurements – in our case, measuring T_{1-3} – were required to fully determine the crutch's kinetic configuration.

To determine the required measurement frequency, we analyzed the force error due to undersampling at various customarily used frequencies. For most robot-assisted movements, peak accelerations are below 1 g. We found that in this case, a measurement frequency of 100 Hz limits the associated error to approximately 2 %. The frequency is also matched to commonly used motion capture systems, facilitating combined data processing. However, for biomechanical analyses that focus on peak or impact forces as outcome measures, higher measurement frequencies of around 500 Hz might be required.

The measurement range along the primary axis of each crutch should resolve loads up to the full bodyweight of a user, or up to 100 kg. For the shear forces, the relevant range was experimentally determined using a standard forearm crutch and a 6-axis force-plate. The range was sized to cover the shear forces that unimpaired participants were able to exert on the force plate by interlocking the cuff and the handle of the vertically positioned crutch. Based on this rationale, required upper force limits of 1000 N in directions along the crutch's primary axis, and of 125 N omnidirectionally in the plane perpendicular to this axis (shear forces) were determined.

Further, the required force measurement accuracy strongly depends on the targeted outcome measure of the specific experiment. For our purposes, we based this requirement on previously found differences between experimental conditions in partial weight-bearing experiments [16]. Here, required accuracies of 10 N for the primary axis force and of 2.5 N for the shear forces were estimated, or 1 % of the full range of the respective axis.

To define the required precision, we considered that robotic experiments are often repeated-measures designs that compare relative differences between, for example, different controllers, rather than absolute values. Thus, we assumed that the required force measurement precision needs to be an order of magnitude lower than the accuracy, or 1 N for all axes over the entire range.

Further, the crutches must not constrain the movement of the user with the wearable robot. Thus, they should be capable of untethered operation and wireless data transmission, with a transmission range of at least 10 m, or the size of a typical biomechanical laboratory. During outside operation, this range would allow for a comfortable margin within which experimenters could follow the user with a mobile receiver unit. To allow for full coverage of typical experimental durations, the crutches should have a minimum battery life of three hours during continuous operation.

Finally, general aspects pertaining to hygiene and maintenance should be considered. All contact surfaces must be simple to disinfect. The crutch tips and handles should be exchangeable to match different user preferences or to allow replacement after prolonged use.

Design and Implementation of the InSight Crutches

The InSight crutches were designed to allow the analysis of arm support during robot-assisted walking in scenarios ranging from standardized laboratory tests to independent field experiments. Therefore, we aimed to combine or exceed the measurement performance previously seen in research-focused devices with the untethered operation and light weight of simpler, therapy-focused devices.

All components used in the InSight Crutches are either commercially available or can be easily reproduced by 3D-printing or in the case of the sensor mounts, with a lathe. An overview of the most important components of the InSight Crutches is presented in Figure 4.

Measurement Technology

The InSight Crutches use an IP-67 sealed 3-axis piezoelectric force sensor (9017C, Kistler AG, Switzerland) which is positioned directly above the exchangeable crutch foot.

The chosen crutch foot (SafetyFoot, Wheelblade AG, Switzerland) has a wider base of support to assure safe use also with heavy wearable robots. In addition, the crutch foot behaves like a joint bearing between the crutch shaft and the ground, leading to level placement of the foot's sole regardless of the crutch shaft position. Therefore, the sensor position directly above the flexible foot circumvents the need for 6-axis force/moment measurements, which would arise for a rigid foot or higher sensor positioning. A 3-component shielded cable is used to transfer the electric charges generated in the piezo-layers of the sensor to an array of three IP-67 sealed charge amplifiers (5030A, Kistler AG, Switzerland). The charge amplifiers have two software-selectable gains (Mode 1 and Mode 2) which allow measurements in two different force ranges (see Table 1). Finally, the signal is then conditioned to a range of 0 to 3.3 V and digitized with a 16-bit analog-to-digital converter.

A 32-bit microcontroller (FRDM K66F, NXP Semiconductors, The Netherlands) running a real-time operating system (FreeRTOS) with a tick frequency of 1'000 Hz is used to process the incoming measurement data. The microcontroller leverages the integrated task prioritization structure of FreeRTOS to perform strictly periodic measurements at a sampling frequency of 100 Hz in the current implementation. In addition, all measurements are combined into a single frame with a local machine time tag directly after acquisition. Thereby, potential processing or transmission delays can be easily compensated for. A low-power, high-performance 2.4 GHz ISM Band wireless transceiver (nRF24L01+, Nordic Semiconductor ASA, Norway) is used to transmit the measurement frames. A receiver auto-acknowledgement and retransmit-function is integrated to minimize data dropouts.

System Integration and Communication

On the receiving end of the InSight Crutch system, we developed two receiver setups to reflect the different requirements during highly-integrated, lab-based testing as opposed to completely untethered standalone experiments (see Figure 5).

Both setups use the same 2.4 GHz ISM Band wireless transceiver (nRF24L01+, Nordic Semiconductor ASA, Norway) that is also used on each of the two crutches. The first setup utilizes an Ethernet-based fieldbus system (EtherCAT, Beckhoff Automation GmbH & Co. KG, Germany) to provide for synchronized real-time measurements potentially involving numerous other measurement systems. The incoming data from both InSight Crutches is transformed to a format suitable for EtherCAT on a 32-bit microcontroller (PIC32MX470F512L, Microchip Technology Inc., USA) and an EtherCAT Piggyback Controller board (FB1111-0142, Beckhoff Automation GmbH & Co. KG, Germany).

The EtherCAT Piggyback controller board combines an ET1100 EtherCAT Slave Controller, two EtherCAT ports and a PDI-connector on a printed circuit board. The PIC-microcontroller is programmed using the EtherCAT Slave Stack Code tool to customize it as an EtherCAT slave device for data acquisition.

In the second setup, the incoming data is directly streamed to a standard PC via a USB-connection. While this option limits the force measurement frequency to 100 Hz for each crutch, it allows to record measurements just using any regular laptop PC.

Additional Considerations for Real-World Use

A digital TTL-Level synchronization port is provided in the form of a 3.5 mm headphone jack. An OpenSDA debugger is integrated into the system and can be accessed via a micro-USB port. To increase the system robustness, wire-connections are mostly replaced with a single custom circuit board that connects the components of the InSight Crutch via printed traces (see Figure 4).

The battery (single cell, 2’800 mAh LiPo) can be charged via a second micro USB port, and easily replaced if necessary. A push-button is integrated on the top face of the crutches’ electronics casing to enable the user to manually start or stop measurements or trigger a “zero-level” routine by long-pressing the button.

Evaluation of System Performance

The measurement performance of the InSight Crutches was verified at an ISO/IEC 17025:2005-certified, independent testing facility (see Figure 6). In brief, the InSight crutch was mounted on a vibration isolation table and continuously loaded along all three principal sensor axes over a range from 0 to 1000 N for the primary axis and of 0 to 150 N for the shear axes. Loads were applied with three hydraulic actuators which were acting in series with 3-axis piezoelectric reference sensors. The crutch foot was removed before testing to allow for more controlled application of forces. Trials were repeated seven times for each axis to allow for an estimation of verification uncertainty. Sensor linearity, hysteresis and crosstalk between the individual sensor channels were calculated for each trial and subsequently averaged over all seven trials.

Our system verification showed that the InSight Crutches' measurement accuracy matches the specified requirement of at most 1 % full scale (FS) error for all axes. Values of 0.38 % FS error for the primary axis and 0.94 % FS error for the shear axes have been obtained (see Table 1). For the shear forces, the result is the average of the two axes.

The larger margin of error for the shear force measurements is mainly stemming from the crosstalk of the primary axis – typically experiencing high loads – to the shear axes, which are typically loaded at lower force levels (see also Table 2). Here, a notable relative error might result even if the relative crosstalk from the primary to the shear axes is generally well controlled. The results of the system verification (details in Table 1 and Table 2) confirm that the InSight Crutches match the specified performance of previous tethered research devices such as [10, 11], while their design inherently allows for mobile field testing and wireless communication.

First Insights from the Lab and from Real-World Scenarios

Building upon the completed technical system verification, the InSight Crutches were used in a series of exemplary case studies involving three robotic systems: the RYSEN [17], an implanted neurostimulator [18] and the Myosuit [19]. The Insight Crutches were used to analyze the role of the arms during movements in which the robotic systems were operated with different control settings or in entirely different control modes.

In the design of the case study series, we considered that wearable technology is increasingly shifting from completely external, primarily rigid exoskeletons over soft exosuits to implanted devices that interface with the neural system of their wearer [20]. With our three chosen robotic systems, we accordingly showcase the added value of the InSight Crutches for a highly relevant range of current and future wearable technology.

Scenario 1 – Walking in a Multidirectional Gravity-Support Robot

Experimental Setup

In the first scenario, the InSight Crutches were used to analyze the vertical, mediolateral and anteroposterior crutch forces of participant S1 (motor-incomplete spinal cord injury at T7 level, >3 years since injury, bodyweight 92 kg) during overground walking in the RYSEN, a multidirectional gravity-support robot [17].

As part of a clinical feasibility study (NCT02936453, see [18]), participant S1 had received an implanted pulse generator that could selectively stimulate the lumbosacral spinal cord to restore voluntary control of previously paralyzed leg muscles. In this scenario, we wanted to evaluate the effect of this targeted neurostimulation and varying levels of body-weight support (BWS) on the participant's arm support.

A set of six passive reflective markers was placed on each crutch and tracked with a system of 14 cameras (VICON, UK). The marker movements were used to transform the measured crutch forces to the lab coordinate system. The crutch measurements were synchronized with the VICON system using an external TTL trigger supplied to the crutches' synchronization port.

Three different conditions were investigated: neurostimulation deactivated with 60 % BWS, neurostimulation activated with 60 % BWS and neurostimulation activated with 40 % BWS. Mean force curves were calculated as average over at least 20 steps for the two conditions with activated stimulation. For the condition with deactivated stimulation, only seven steps could be captured before the participant fatigued.

Results and Discussion

We expected the neurostimulation to improve voluntary muscle control of the leg muscles, thereby allow for more weight-bearing through the participant's legs, and hence reduce the vertical crutch forces.

Without stimulation, the participant unloaded approximately 19 % of his bodyweight (BW) with each crutch (see Figure 7). Once stimulation was activated, a mean reduction of 8.3 % BW for the left crutch and 4.4 % BW for the right crutch was observed. The effects on the mediolateral forces were similar. We interpret this observation as an effect of the increased weight-bearing capacity and improved balance due to the active neurostimulation.

Further, the mean anteroposterior forces were reduced to nearly zero when the neurostimulation was activated, suggesting that the participant could walk without compensatory propulsive efforts through the arms once intrinsic leg advancement was enabled by the stimulation. Without neurostimulation, the participant appeared to pull himself forward at the beginning of crutch ground contact (see Figure 7).

In the third experimental condition, we found that upon a reduction of BWS from 60 % to 40 % BW, crutch forces along all axes increased. While this effect was generally expected, the magnitude of the crutch force increase (5.4 % BW left, 5.0 % BW right) shows that half of the reduced unloading was compensated for through the arms. Consequently, the mean load on the legs must have only increased by about 10 % BW.

Apparently, the participant distributed the additional gravitational load of 20 % BW almost equally between his arms and his legs. Therefore, training protocols should carefully consider the balance between loading the legs by reducing BWS and the achievable training duration before fatigue of the arms. One can speculate that for some severely affected participants such as S1, lower BWS can reduce the overall training intensity because of shorter training durations. In the future, it will be interesting to use the InSight Crutches to investigate if this observation can be confirmed in more participants and eventually relates to the recovery of motor function.

Scenario 2 – Sit-to-Stand Transfers with the MyoSuit

Experimental Setup

In a second experiment, the InSight crutches were used to analyze the vertical, mediolateral and anteroposterior crutch forces of participant S2 (motor-incomplete spinal cord injury at C5 level, >25 years since injury, bodyweight 79 kg) during sit-to-stand transfers in a laboratory environment.

Participant S2 was wearing a lightweight, mostly soft wearable robot, the MyoSuit Alpha, which is an improved version of the device described in [19]. In one condition, the MyoSuit actively supported hip and knee extension ("Assist. ON"). In a second condition, the motors were actively controlled such that the linear cable forces were always below 20 N, but the cables would never slack (referred to as "Assist. OFF" here, also "transparency mode" in [4]).

In this scenario, we wanted to evaluate the effect of the assistance from the MyoSuit on the crutch force magnitude and loading duration during sit-to-stand transfers. As a proof-of-concept for more complex laboratory-based testing applications, the crutch forces were recorded using the EtherCAT interface (see Figure 5).

A set of six passive reflective markers was placed on each crutch and tracked with a system of 19 cameras (VICON, UK). The marker movements were used to transform the measured crutch forces to the lab coordinate system. The crutch force measurements were synchronized with the motion capture data internally within the EtherCAT system. Mean force curves were calculated as an average over four repetitions for each condition. The conditions were tested in an alternating sequence to limit the effect of fatigue.

Results and Discussion

We expected the active assistance from the MyoSuit to enable the participant to stand up faster than without assistance and hence to reduce the crutch impulse during sit-to-stand transfers.

The time the participant needed to transfer from sitting to standing when actively assisted by the MyoSuit was reduced to about 50 % of the time required without assistance (see Figure 8). The peak forces in vertical direction were approximately similar between the two conditions. However, this peak force was observed as a well-defined peak with assistance, but over a prolonged period without assistance. An analysis of synchronized video recordings reveals that during this period, the participant struggled to achieve full knee extension without assistance.

In line with our expectation, the total crutch impulse during sit-to-stand transfers was reduced by 52 %. Further, a trend towards reduced mediolateral support forces was observed when the MyoSuit actively assisted the participant, indicating a more stable movement. Our findings confirm that the assistance from the MyoSuit was effective in facilitating sit-to-stand transfers for the case-study participant.

Scenario 3 – Outside Walking with the MyoSuit

Experimental Setup

In our third scenario, the InSight Crutches were used to analyze the total crutch impulse of participant S2 during outside walking.

Participant S2 used the same wearable robot as in scenario 2, the MyoSuit. The MyoSuit was again used in two different control modes (“Assist. ON” and “Assist. OFF”) as described in the experimental section of scenario 2.

As a proof-of-concept for standalone outside testing, the measurements were performed only using the InSight Crutches and a standard laptop PC with a small receiver board (see Figure 5). Importantly, no additional spatial tracking was required in this scenario because our primary outcome measure, the total crutch impulse, could be calculated from 3-axis force measurements represented in any reference frame.

The participant completed four runs of 25 m length each. To limit the effect of fatigue, tests were performed in the order Assist. OFF, Assist. ON, Assist. ON, Assist. OFF. After each run, the participant was questioned about his perceived exertion using the Borg Scale questionnaire. A pause of two minutes was taken between runs.

Results and Discussion

We expected the anti-gravity assistance during stance to reduce both the force magnitude during and the duration of crutch contact with the ground. Such a reduction would result in a lower total crutch impulse.

The total crutch impulse was reduced by 70 % (left crutch) and 63 % (right crutch) when the MyoSuit assisted the participant compared to no assistance (see Figure 9). A higher total crutch impulse was observed for the participant's left crutch compared to the right crutch. This asymmetry is consistent with the participant's self-reported lower strength in the right leg. In a 2-point crutch gait, the right leg and the left crutch share the weight-bearing during stance phases. Thus, a weaker leg would additionally load the contralateral crutch. Such individual participant characteristics are important to consider, e.g. during future personalization of the assistance from the MyoSuit.

The current assistance from the MyoSuit enabled the participant to increase his walking speed from 0.44 m/s to 0.70 m/s. At the same time, the perceived exertion, measured by the Borg Scale, was reduced from 15 to 9.5. These results suggest that the MyoSuit effectively assisted the case-study participant during overground walking.

Conclusions

In this article, we discussed the technical and practical requirements for an instrumented walking aid that can be used in the field of wearable robotics. Based thereon, we developed and evaluated the InSight Crutches. A systematic verification at an independent testing facility confirmed that the measurement accuracy of the InSight Crutches matches our pre-defined requirements. In a subsequent case study series, the InSight Crutches were successfully used to quantify the arm support of habitual crutch users with incomplete spinal cord injury, as they received different types of wearable robotic assistance.

Previous research had shown that targeted neurostimulation of the lumbosacral spinal cord can re-establish voluntary control of paralyzed leg muscles during walking [18]. In scenario 1, the InSight Crutches were used to show that the targeted neurostimulation also reduced weight-bearing as well as compensatory balance and propulsive efforts through the arms.

Further, the InSight Crutches showed potential as a tool to modulate the overall training intensity during walking with a gravity-support-robot. Here, the crutches could provide information about the optimal balance between the loading of the legs and the loading and hence fatigue of the arms that might limit the achievable training duration.

In scenario 2 and 3, the InSight Crutches were used to show that assistance from a soft wearable robot for the legs, the MyoSuit, reduced the required arm support through crutches of a participant with spinal cord injury during sit-to-stand transfers and during outside walking. The robotic assistance enabled the participant to perform the movements faster while his perceived effort was reduced.

In each scenario, the InSight Crutches provided crucial information for the validation of purported benefits of wearable robotic assistance, for its further optimization, or about participant behavior. Thereby, our scenarios illustrate the manifold ways in which instrumented crutches can and should be used in wearable robotics research and development.

With our choice of scenarios and wearable robots, we extend beyond the conventional notion of rigid exoskeletons towards soft wearable devices like the MyoSuit and neural interfaces such as the implanted stimulator. Experts believe that these device categories will become increasingly important in the future of wearable robotics [20]. Our findings demonstrate that systems like the InSight Crutches can add important information about these devices' real-world dynamics, the human-robot interaction, and the resulting human user performance.

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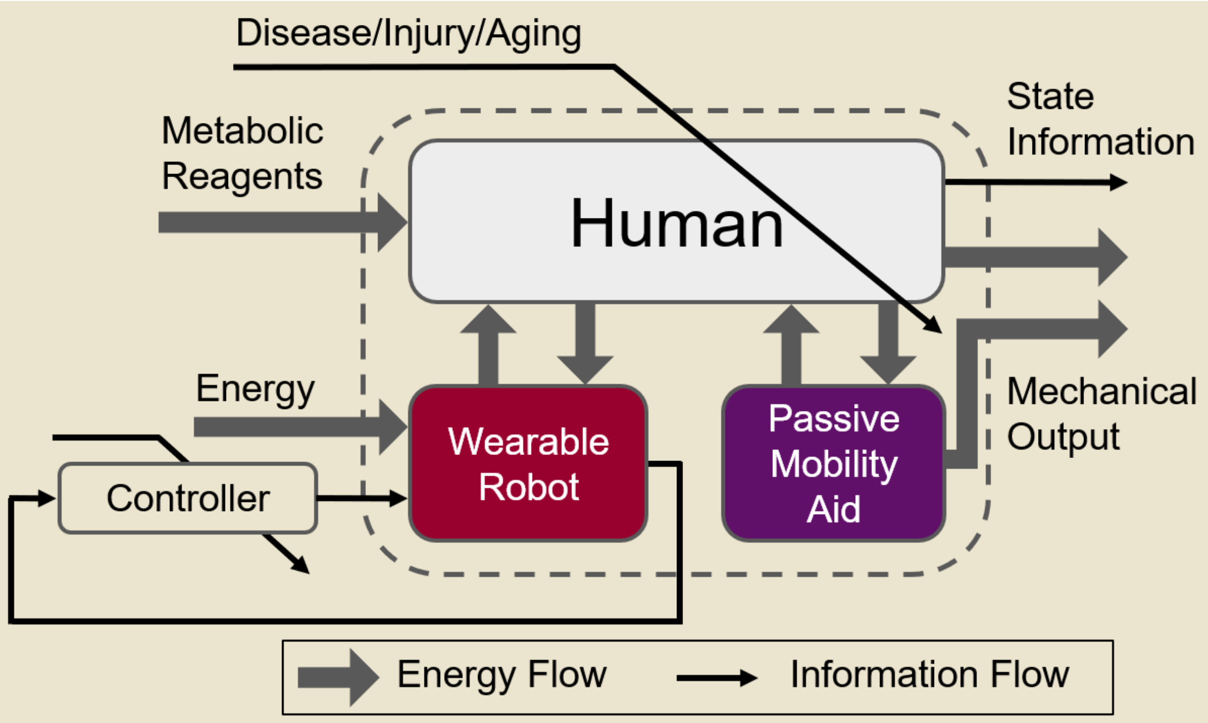

Figure 1. Most wearable robots for users with a leg weakness require additional support for balance and weight-bearing. This support is typically provided through the arms via handheld passive mobility aids like crutches. Hence, users interact with their environment in parts directly with their own body, and in parts through the passive mobility aid.

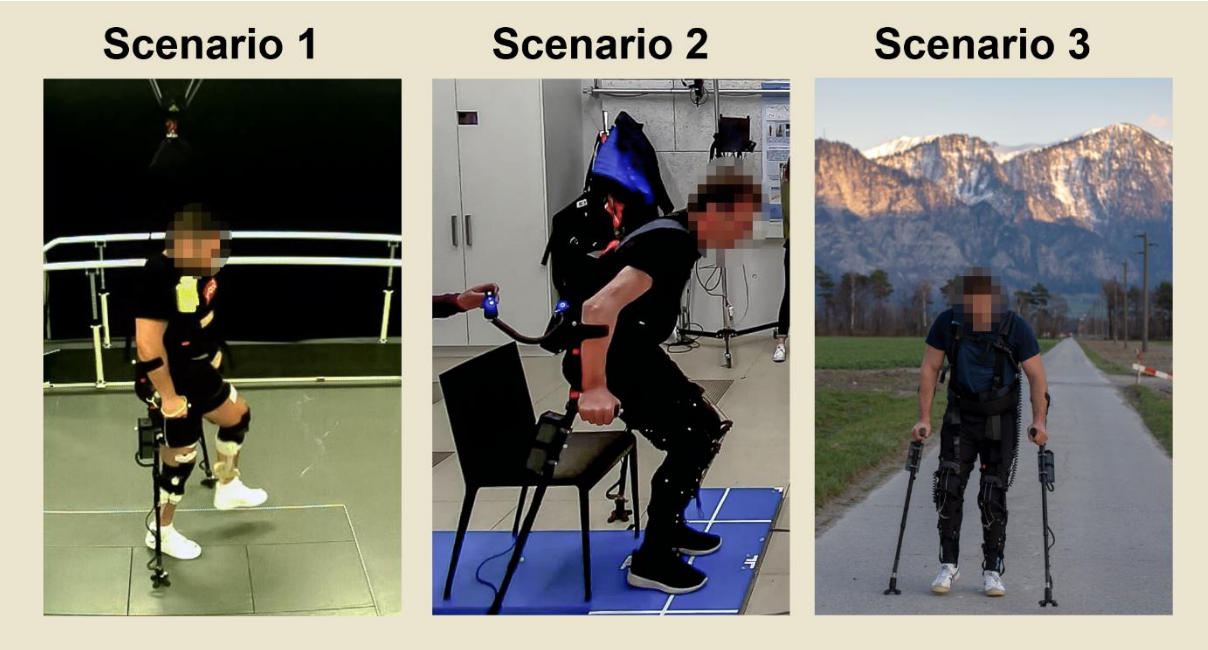

Figure 2. To advance the understanding of how wearable robots function, it is essential to quantify the arm support during movements. In this article, we provide first insights into exemplary scenarios ranging from gait training in a gravity-support-robot with active neurostimulation (scenario 1), over biomechanical evaluations of robotic assistance during activities of daily living (scenario 2), to robot-assisted outside walking (scenario 3) with spinal-cord-injured participants.

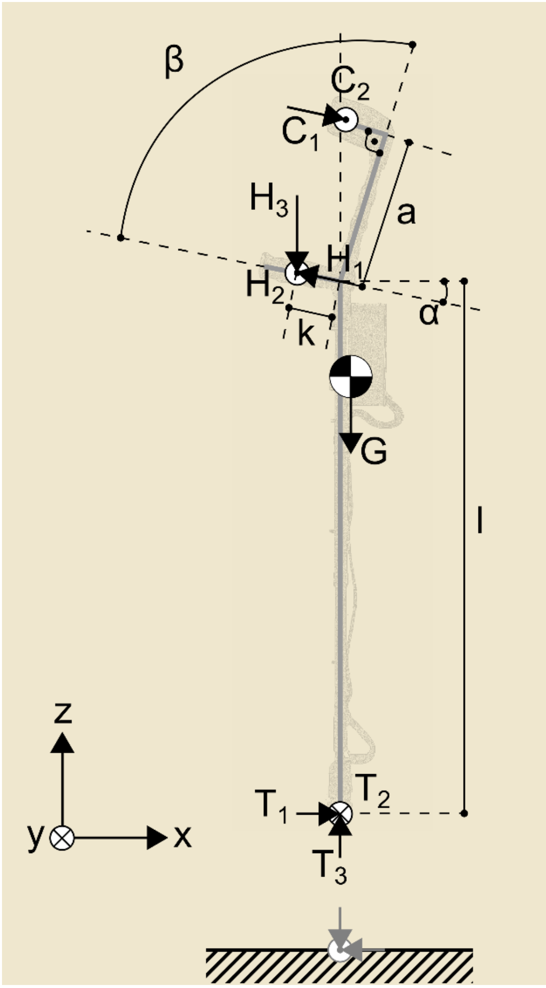

Figure 3. Free-body diagram of a forearm crutch. A total of eight interaction forces with the environment and a gravitational force are considered. The crutch geometry is described following EN ISO 11334-1:2007.

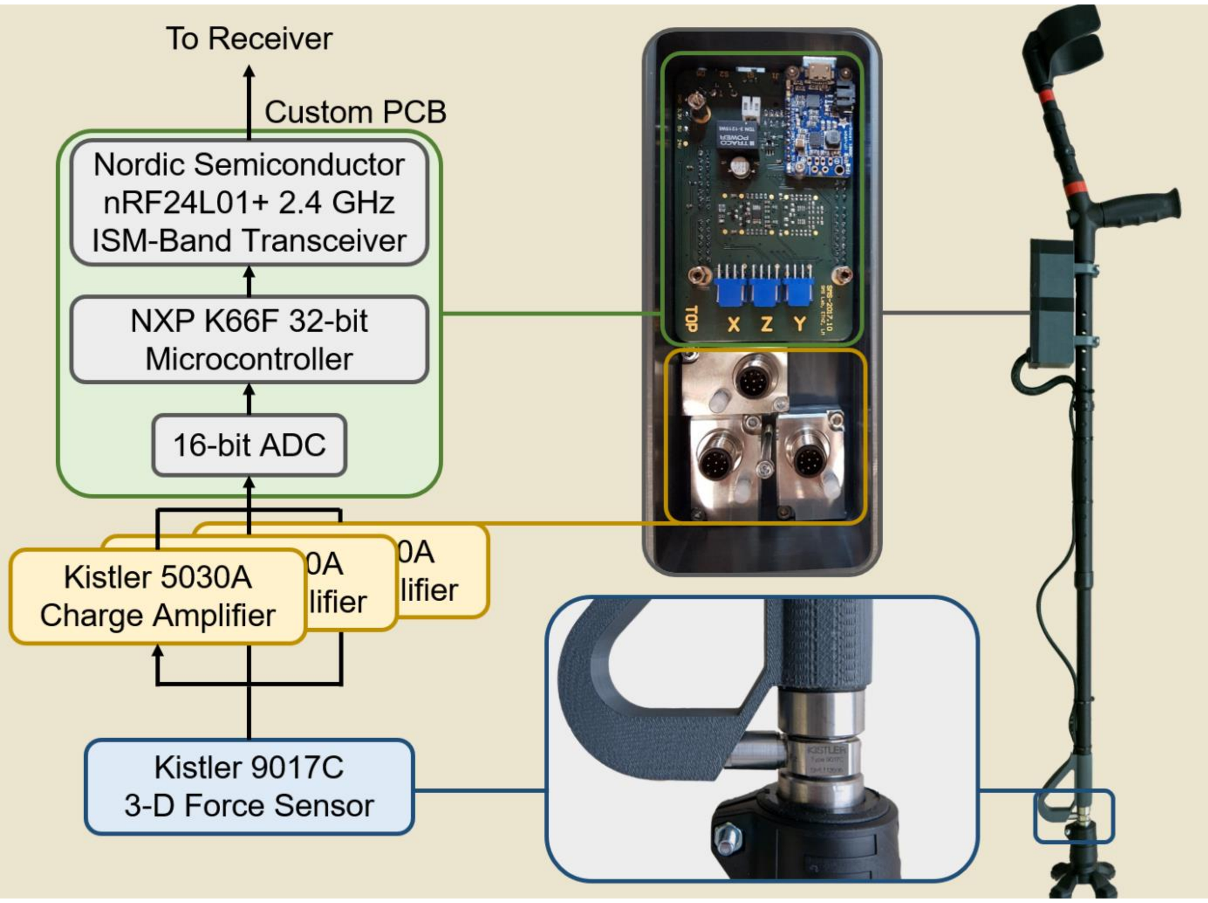

Figure 4. Design overview of the InSight Crutches. A 3-axis, piezoelectric force sensor is integrated into a commercial heavy-duty crutch directly above the foot. All components that require a power supply are contained within the detachable case on the back of the crutch. Following amplification and digitization, the measured forces are transmitted to a receiver board.

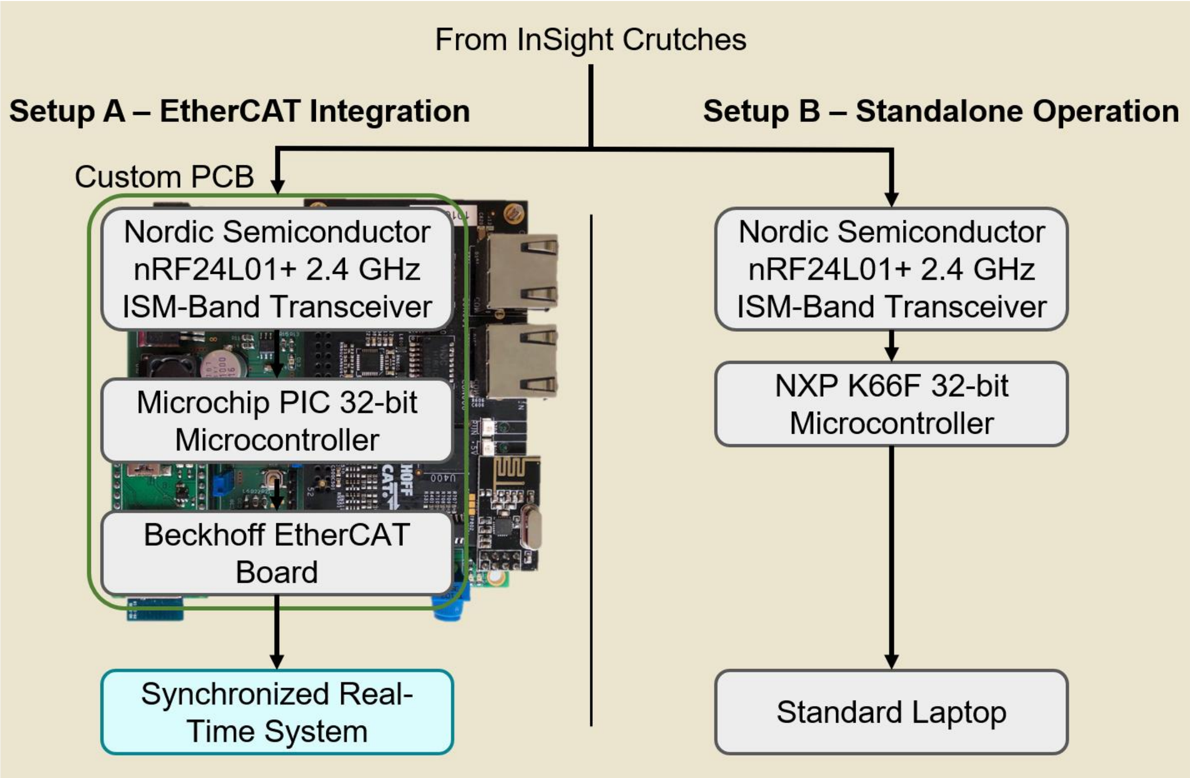

Figure 5. Design overview of the two interfacing setups for the InSight Crutch system. For synchronized real-time measurements, the InSight Crutches can be integrated with an EtherCAT system via a custom-designed printed circuit board (Setup A). For standalone operation, e.g. during mobile measurements, the Insight Crutches can provide a wireless data stream to a standard laptop via an external microcontroller board (Setup B).

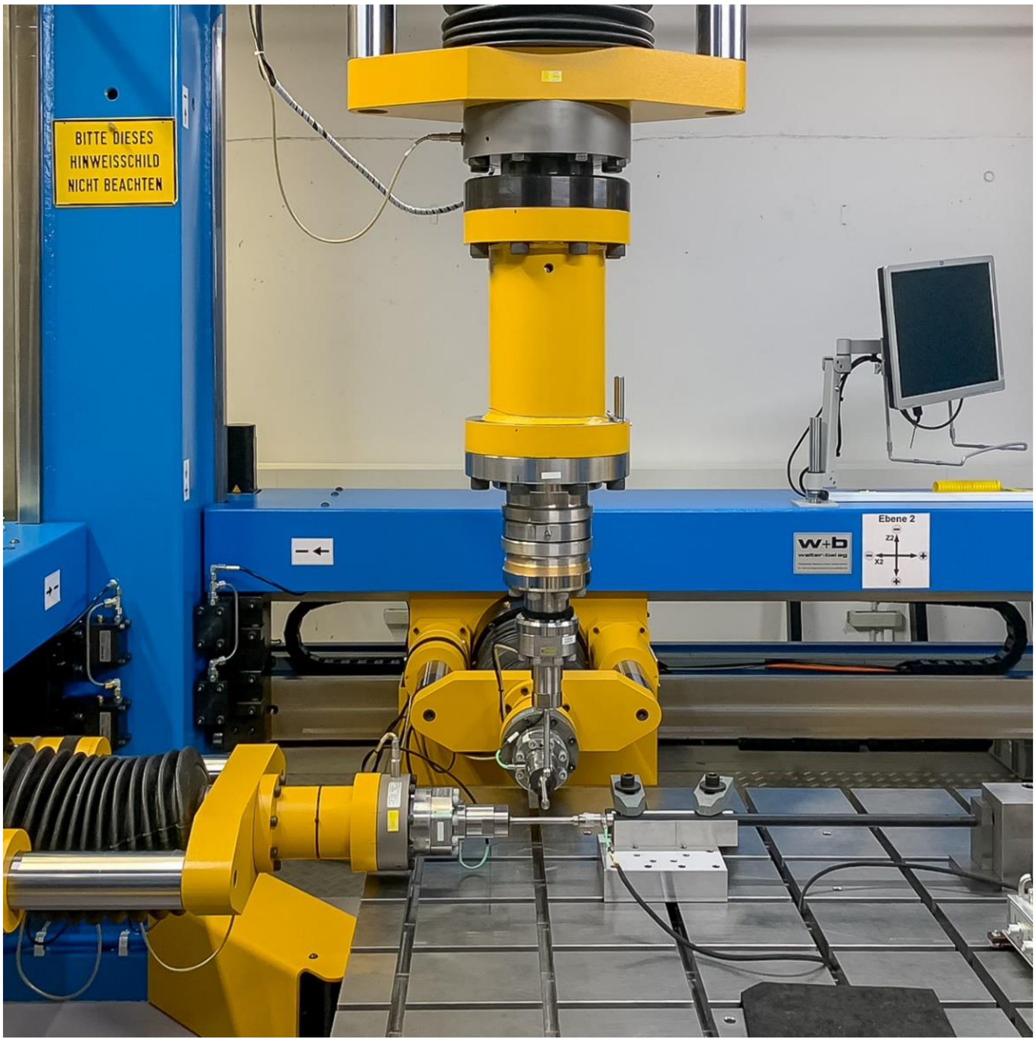

Figure 6. Picture of the system verification setup. Three independent, hydraulic actuators (yellow) with integrated 3-axis load cells were used to load the InSight Crutch which was horizontally attached to the test table. The crutch foot was removed before testing to allow for more controlled application of forces.

Table 1. Summary of requirements of an instrumented crutch system for use with wearable robots and overview of the physical characteristics, sensory performance and operational performance of the InSight Crutches.

Characteristic	Requirements	InSight Crutches	
Practical considerations			
• Use validated, commercial sensor technology • Clean appearance, minimized clutter • Simple disinfection of contact surfaces • Replaceable tips and handles			
Physical requirements			
Handle height from ground	75-100 cm (adjustable)	73-103 cm (adjustable)	
Max. loading	150 kg	150 kg	
Max. weight	1.5 kg	1.435 kg	
Center of mass	directly below handle	close below handle	
Sensory requirements			
Measured force axes	3-axis	3-axis	
Min. sample rate	100 Hz (500 Hz)	100 Hz (1 kHz w/ EtherCAT)	
Primary force			
Range	0…1000 N	Mode 1 Mode 2	0…929 N 0…3'000 N
Resolution	100 mN	Mode 1 Mode 2	14 mN (10 mN disp.) 140 mN (100 mN disp.)
Accuracy	1 % Full Scale (FS)	0.38 % FS incl. linearity, hysteresis and crosstalk	
Precision	1 N	0.5 N[1]	
Shear forces			
Range	-125…125 N	Mode 1 Mode 2	-122…122 N -1'222…1'222 N
Resolution	100 mN	Mode 1 Mode 2	4 mN (10 mN disp.) 40 mN (100 mN disp.)
Accuracy	1 % Full Scale (FS)	0.94 % FS incl. linearity, hysteresis and crosstalk	
Precision	1 N	0.5 N	
Operational requirements			
Min. hours of autonomy	3 h continuous	> 3 h continuous	
Communication	wireless, range > 10 m	wireless, range > 15 m	

[1] This value is calculated as the size of the 95 % confidence interval for repeated measurements at the same load level.

Table 2. Experimentally determined linearity, hysteresis and crosstalk between sensor channels. Values are given as (mean error) ± (std. dev.) over seven repeated measurements for each channel.

Channel	Linearity	Hysteresis	Crosstalk to X	Crosstalk to Y	Crosstalk to Z
Z (primary)	0.06±.01 %	0.06±.01 %	-0.04±.01 %	0.11±.01 %	
Y (shear)	0.23±.02 %	0.38±.02 %	-0.52±.05 %		-0.02±.06 %
X (shear)	0.21±.02 %	0.34±.05 %		0.70±.01 %	2.80±.05 %

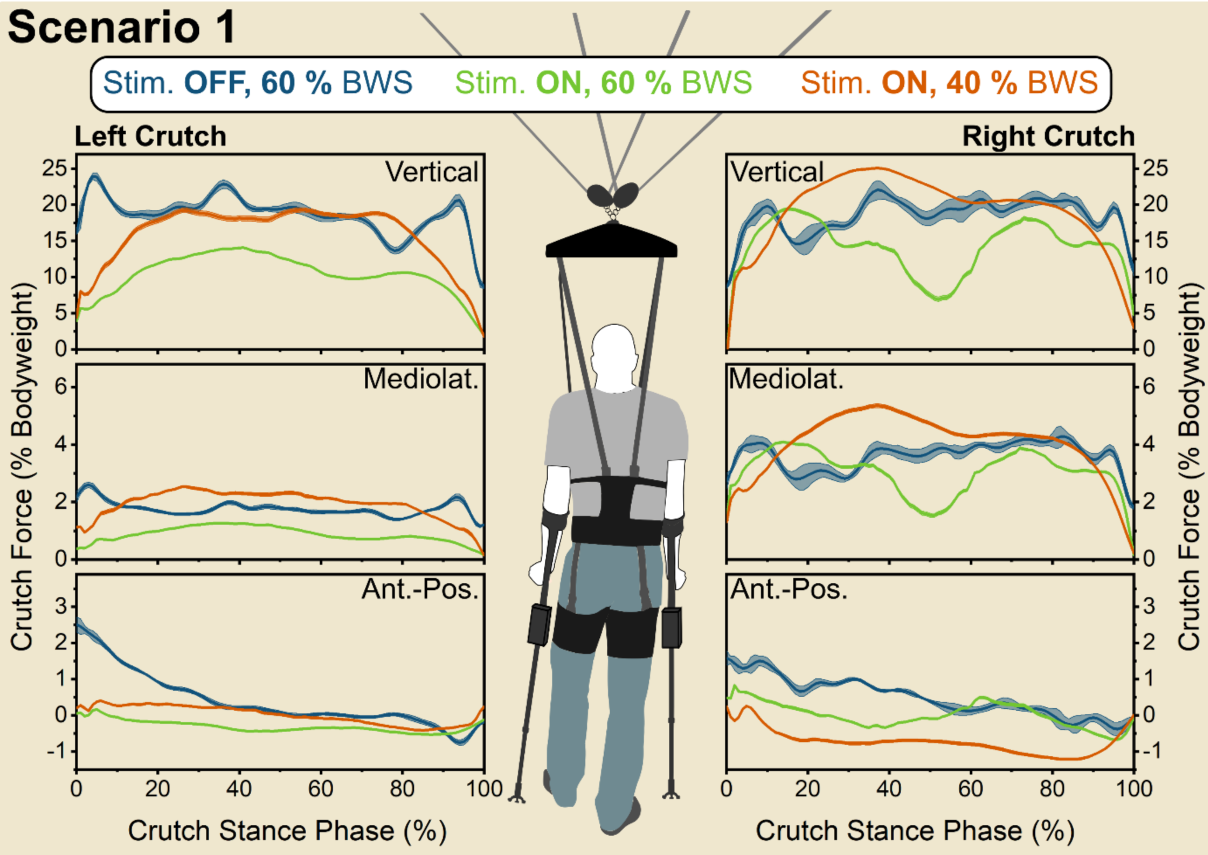

Figure 7. In scenario 1, we analyzed the crutch support of a participant with a severe incomplete spinal cord injury and an implanted targeted neurostimulator during walking in a gravity-support robot. Three different conditions were investigated: One in which the neurostimulator was turned off and 60 % body-weight-support (BWS) was provided from the robot, one in which the neurostimulator was active at the same level of BWS, and one in which the neurostimulator was active and BWS was reduced to 40 %. The curves represent means that were calculated over at least 20 steps for Stim. ON conditions and over seven steps for Stim. OFF. The standard error of the mean is provided as shaded area around the mean curves.

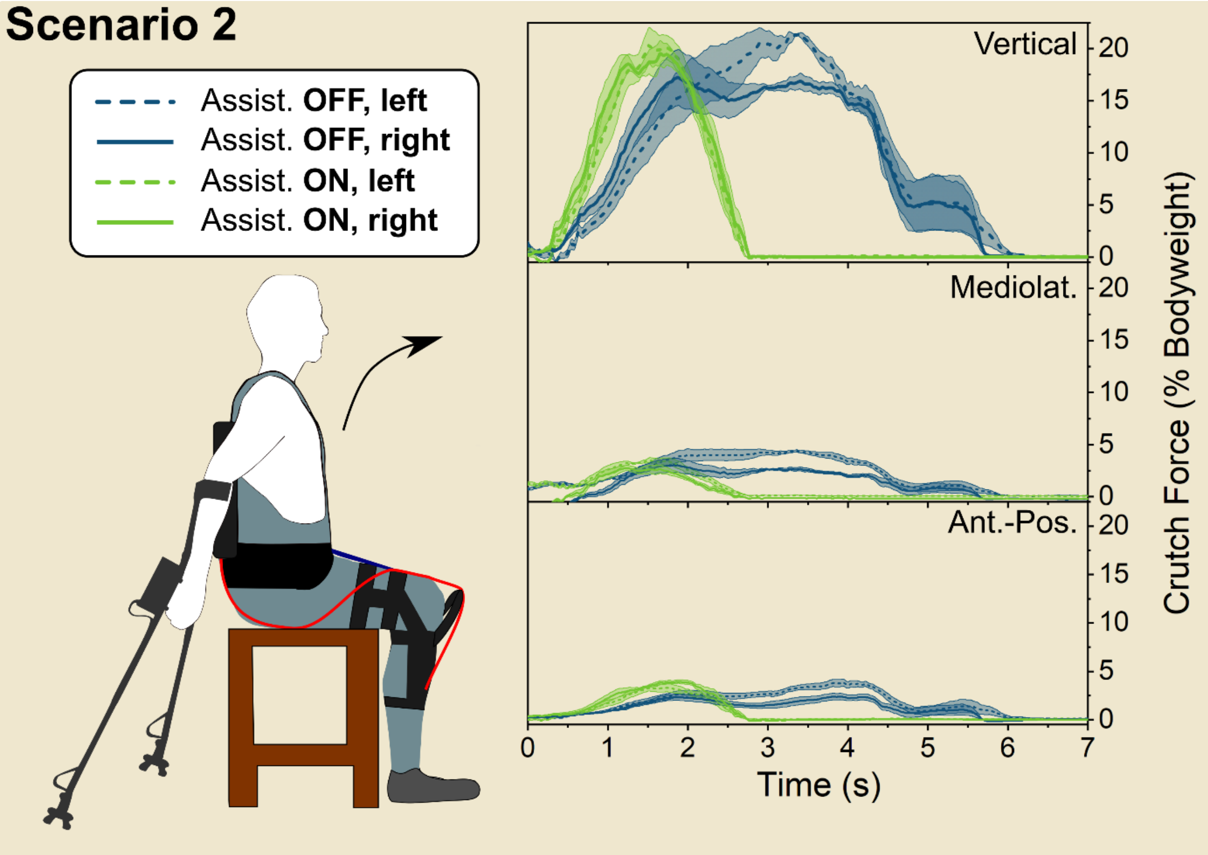

Figure 8. In scenario 2, we analyzed the crutch forces that a participant with an incomplete spinal cord injury exerts during sit-to-stand transfers from a typical chair. A comparison between transfers that were assisted by a soft wearable robot, the MyoSuit, (Assist. ON) and ones that were not assisted (Assist. OFF) is made. The curves represent means that were calculated over four repetitions each for Assist. ON and Assist. OFF. The standard error of the mean is provided as shaded area around the mean curves.

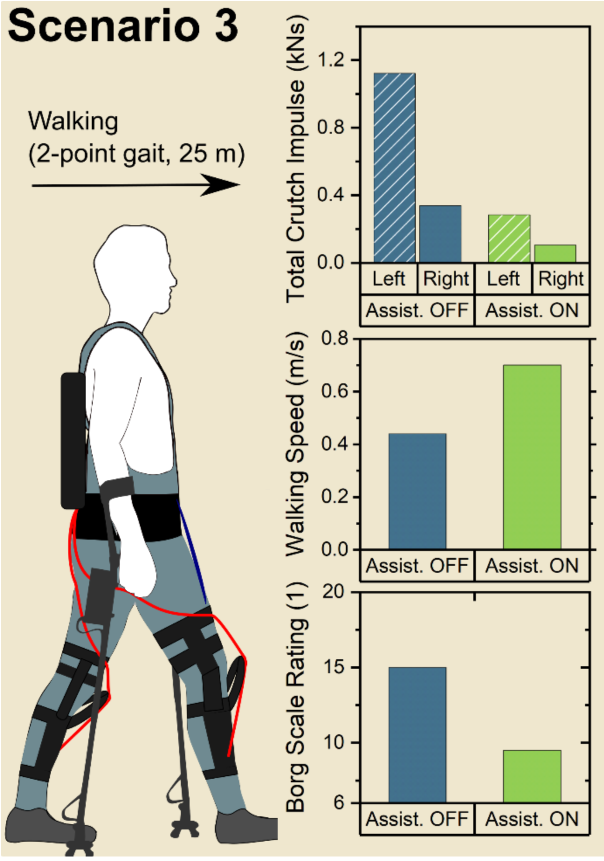

Figure 9. In scenario 3, we analyzed the total crutch impulse, the average walking speed, and the self-reported exertion during four repeated runs of outside walking for a participant with incomplete spinal cord injury. During two runs, the participant received anti-gravity support from a wearable robot, the MyoSuit (Assist. ON). During the two remainder runs, the MyoSuit was actively driven to minimize cable and hence assistive forces (Assist. OFF). Results are presented as mean of the two respective runs.