A Graphical User Interface for Individualized Locomotor Training of Infants With or at High Risk of Cerebral Palsy Using a Robotic Assistive Device

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Abstract

Background

Precision rehabilitation is essential to optimally meet the specific needs of children with developmental motor disorders such as cerebral palsy (CP). While assistive devices are useful tools for motor training by supporting the child, augmenting actions, and encouraging practice, these devices often have limited sets of predetermined, fixed modes of interaction and parameters that can limit the effect of their responses to performance.

Objective

We present the design of a graphical user interface (GUI) that facilitates prone locomotor learning and monitoring of individualized learning efforts by infants using a robotic assistive crawling device.

Methods

The Self-Initiated Prone Progression Crawler (SIPPC) robot engages sensor-driven interaction and incorporates motor learning and precision rehabilitation principles to encourage and assist early prone locomotion. Training on the SIPPC is 12–16 weeks, with hands and feet contacting the floor. Infant and robot data are displayed in the GUI, where therapists monitor infant performance and robot behavior. Through the GUI, therapists can make real-time adjustments in the robot response to infant movements, thereby increasing opportunities for successful movement at any learning stage. Selectable robot control modes either respond to infant-generated ground reaction forces (force control) or limb gestures (G1 and G2). The GUI enables control mode response threshold and magnitude adjustments, and provides scripted session guidance and data management.

Results

Preliminary results show therapists can provide real-time configuration changes to the SIPPC response type, sensitivity, and magnitude based on infant skill, mood, and effort. Infant and robot behavior are observed concurrently with these configurations. Therapists enable force control and G1 for most sessions. G2 detects more coordinated limb gestures than G1 and used during later sessions after infants have more practice and SIPPC experience. During early therapy sessions, therapists change parameters multiple times throughout the trials. In subsequent weeks, therapists typically adjust parameters at the trial beginning.

Conclusion

Individualized intervention is important for optimizing rehabilitation outcomes. Our interface design allows therapists to customize the assistive robotic responses to each infant's needs and learning style to promote motor learning specific to each infant's motor function. This innovative approach allows precise monitoring of movement learning across time and infants, offering additional value to measuring infant locomotor development.

Keywords

motor learning, motor training, motor control, assistive therapy robotic systems/devices, crawling skill acquisition, prone progression, cerebral palsy (CP)

Introduction

Cerebral Palsy (CP) is a group of developmental motor disorders in infants that results in lifelong impairment and can impact the progression of locomotion, cognition, perception, communication, and behavior [1–3]. Impaired motor control and coordination in infants with CP can vary across individuals and produce challenges to motor learning and skill acquisition, leading to delayed or missed developmental milestones, such as crawling [4, 5]. Early diagnosis and intervention are therefore crucial for infants at high risk of CP to leverage neural plasticity and neural pathway pruning early in life [2–7].

Crawling is a profound milestone in development for most typically developing infants; acquisition of this milestone influences muscular strength, motor coordination, and cognitive development [8–10]. Typically, infants learn to crawl by moving through a sequence of developmental stages, progressively increasing the magnitude and coordination of their movements [11, 12]. When placed prone, they initially learn to lift their heads for increasing duration to observe their surroundings and to identify objects of interest. As they obtain more strength and control over their trunk and limbs, they start to shift their weight and reach for nearby objects. With increasing muscle strength and coordination, they start moving around on their stomachs, before transitioning to quadrupedal motion on their hands and knees. With further refinement of limb and trunk control and coordination, they can move in their environment toward toys and other objects of interest. However, challenges such as reduced muscle strength or control can result from disorders like CP and make achieving any of these stages unassisted much more challenging [1–3, 13].

Activity-based interventions can potentially improve motor function by targeting multiple motor performance components, such as endurance, coordination, and strength, with varied levels of intensity and frequency to provide individualized rehabilitation [3, 4, 7, 14]. For example, passive range motion exercises can help prevent or reduce joint contractures and low resistance high repetition exercises can help with muscle strengthening and endurance [3]. Morgan et al. [7] developed the Goals-Activity-Motor Enrichment (GAME) therapy approach to promote early, intense, environmentally enriched, task-specific, home-based training for motor and cognitive skill improvement in infants with CP. In the GAME paradigm, therapists and caregivers work together to adjust the infant's environment to promote successful self-generated motor activity. While temporary performance improvements are motivating in therapy, it is crucial to ensure advancements in motor capabilities are permanent and applicable to active daily life. To do so, is useful to increase motor challenge as performance improves to help solidify learned problem-solving capabilities and skill generalization [7, 15, 16].

While therapeutic interventions can aid individuals in learning motor skills to navigate their environments or to learn tasks necessary for daily activities [17, 18], there is often a high variability in individual responses to intervention [19] and some variation in therapist implementation of intervention procedures [13, 14]. Therefore, interventions should consider the unique dispositions of each individual and be adjustable to best address their personal needs and limitations. And, these adjustments should be quantitative to allow for consistency and objective comparison between alternative therapist implementations.

Figure 1 summarizes a model of the dynamic, real-time interaction between the environment, device, learner, and therapist. Through a feedback loop, the device augments the learner's capacity to explore the space of relevant constituent motor actions with differing complexities. The therapist can observe the activities of the learner and respond by altering the learner's environment. In addition, the device provides detailed information about the performance of the learner to the therapist, who, in turn, tunes the response of the device to meet the learner's specific needs.

In this context, an assistive therapy device that applies to a range of motor deficits of varying severity levels should adhere to the following *design principles*:

1. support learning of a range of skills of varying complexities,

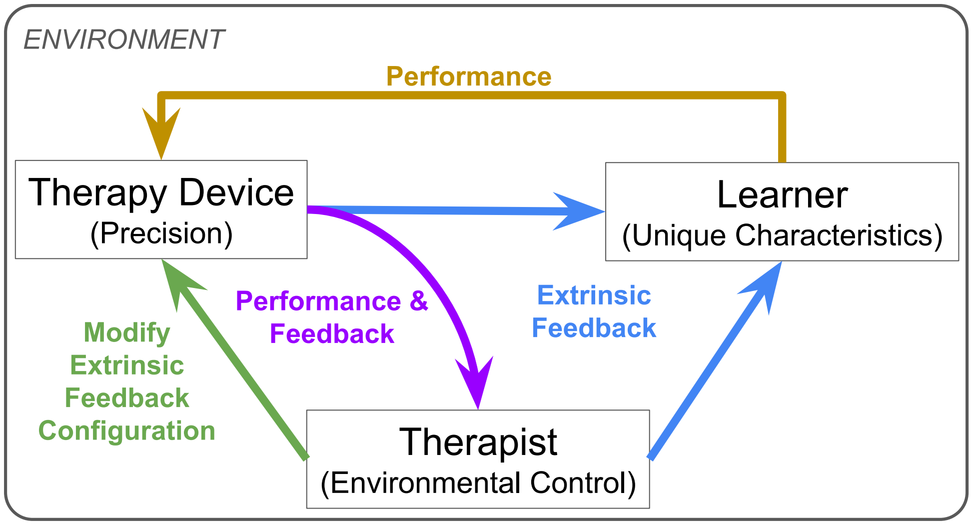

Figure 1: Flow of extrinsic feedback. In natural environments, there is a feedback loop between the environment and the learner. Without an assistive therapy device, the therapist acts as a mediator between the environment and the learner by controlling the configuration of the environment and how the learner interacts with it. With a therapy device, both the learner and the therapist obtain feedback from the device, and the therapist can modify the configuration of that feedback. The assistive therapy device acts as an additional mediator with the environment. Additionally, the device can respond in real-time to the performance of the learner without waiting on input from the therapist. In this study, the SIPPC is the device and the infant is the learner.

2. provide automatic extrinsic feedback to the learner through repeatable assistance that is contingent on the learner's performance in real-time, and

3. provide extrinsic feedback to the therapist to allow objective performance assessment and to adjust the learner-device interaction.

The first design principle addresses the variation in motor capacity of individuals with motor disorders. Assistive devices can augment and provide some enhancements to individual movements. This can help learners practice and build new motor skills. Additionally, the device helps the learner identify and engage effective skills related to desired motor objectives. Because CP can impact motor capability in many ways, it is crucial to have devices that are capable of supporting the practice and achievement of a large set of skills appropriate to the individual's level of motor function.

The second design principle requires that the device provide extrinsic feedback to the learner in real-time in response to the learner's performance. Moinuddin et al. [20] defines feedback, in the context of motor learning, as information "fed back" to the learner as the result of movement. The feedback can be sent before, during (real-time) or after the action to inform motor adjustments in preparation for subsequent actions. Real-time feedback is important to allow the learner to quickly change strategy and to determine the relationship between certain actions and progress towards a goal [4, 16]. Solidification of learning through quality repetitive practice is a core component of effective therapy and motor learning [17, 18, 20]. Salmoni et al. [15] and Kitago and Krakauer [16] discuss the temporary impacts of extrinsic feedback (knowledge of results; KR), and that reducing or removing KR in later stages attenuates the temporary performance effects of the feedback and accentuates lasting, transferable improvements that are actually due to learning. This form of real-time extrinsic feedback can provide infants at risk of CP with high-frequency training and help implicitly communicate learning objectives to infants since they are not able to follow instructions and verbally communicate.

The third design principle requires that the device provides qualitative and quantitative feedback to the therapist. It is paramount that therapists have objective knowledge about the status, progress, and trajectory of the learner. This knowledge empowers the therapists to make informed decisions for the learner's experience. Upon receipt of the feedback, the therapists can alter the feedback response to future actions during the same session. Modifying the feedback in real-time enhances the therapist's ability to affect behavior and guide learning. Changes in feedback can serve to motivate activity or encourage the exploration of various sets of underutilized actions (e.g., encouraging infants who struggle to move one particular arm to begin engaging it to reach for toys). As the learner improves, the therapist should be able to modify the feedback to increase the challenge and prevent primary dependency on the feedback. Moreover, if the learner is not successful, the therapist can decrease the challenge to provide successful feedback to the learner.

Assistive devices (e.g., walkers, gait trainers, exoskeletons, robotic devices) can be used in therapy to augment and enhance motor performance by enabling exploration and discovery in various environments [3, 13, 14]. The combined extrinsic feedback from the environment and an assistive device can help learners adapt, evaluate the utility of various motor strategies [21], and improve overall motor function [3]. Assistive therapy devices can also be useful tools for augmenting the interaction between the therapist and the learner. Through a combination of sensors, functional user interfaces, and robotics, these devices have the potential to offer therapists more quantitative information, control, and flexibility when making therapy decisions, while simultaneously providing feedback and assistance to train the learner. However, such devices are often limited in applicability and availability for children, especially infants, due to differences in needs between children and adults. Moreover, assistive devices for infants that support early learning of locomotor skills, such as crawling, are not widely available [22, 23], do not provide performance feedback [24, 25], or do not offer a flexible set of parameterized controls for the therapist [24–26].

The Self-Initiated Prone Progression Crawler (SIPPC) robot is a unique assistive crawling device that is designed to promote movement learning in infants with motor delays by offering an array of crawling-based movement strategy options [21–23, 27]. The SIPPC supports the weight of the infant in a prone posture in which their hands, feet and knees can contact the floor. The robot can carry the infant along a combination of forward and turning paths – contingent on the ground reaction forces (GRFs) or the limb movements (LMs) produced by the infant. For example, if the infant pushed against the floor to the left with their two hands, the SIPPC would respond by turning the infant to the right (GRF). Or, if the infant made a pulling motion with their hands from in front of their body toward themselves, even without contacting the floor, the SIPPC would move the infant forward (LM).

Kolobe and Fagg [21] investigated the effects of these response contingencies with three groups of infants: typically developing infants with GRF-based responses (TD), infants at risk for CP with GRF-based responses (GRF), and infants at risk for CP with both GRF and LM responses (GRF+LM). Over bi-weekly exposure to the SIPPC for 12–20 weeks, the TD group demonstrated a greater increase in the magnitude of arm movements and in trial-and-error activities over both at risk groups. In addition, among the at risk groups, the GRF+LM group demonstrated an advantage in these metrics over the GRF group. This indicates that the SIPPC with appropriately selected response contingencies can contribute to motor exploration and to learning new motor skills. However, the fixed contingencies by group can present limitations on an individual basis. Adding the LM contingency on top of the GRF contingency can make the SIPPC easier for the infant first to learn to engage the robot in producing purposeful movements, but does not necessarily challenge the infant to refine their skills further. On the other hand, the GRF-only contingency is more challenging to the infant, but to a degree that can impede the first learning steps.

For the SIPPC (and other therapeutic devices) to meet the unique needs of more individuals, it is important to provide the therapists with the ability to dynamically select contingencies, in addition to tuning their details, in an individual and context-dependent manner. A key challenge is choosing this set of contingencies and their associated parameters, and then presenting these options to the therapist in a manner that facilitates (and not impedes) their interaction with the patient. Many existing therapy devices possess user interfaces that operate as a control center for the therapy session to adjust the exercises based on therapy goals, the patient needs [28–30], and they take steps to promote understandability, reliability, and accessibility [30, 31]. Octavia et al. [28] designed Matti, an interactive gaming mat that uses a tangible user interface (TUI) to support motor rehabilitation for children with developmental coordination disorder (DCD). Here the TUI is designed to engage and motivate the patient and a screen displays visual feedback from therapy games. A separate graphical user interface (GUI) is provided to the therapists to select games and adjust configurations based on the therapy goals. One limitation of this design is that once the therapist begins the therapy game, the configuration is fixed until the game is complete or terminated. This can limit practice opportunities that optimally address the child's unique motor function and skill level. In work by Tucker et al. [29], they developed a GUI for wireless operation and data logging from a robotic knee exoskeleton for children with CP. The interface allows users to select and configure two control modes and automatically enforces the order of procedural therapy operations to reduce the chance of error. Despite the capabilities of the exoskeleton and GUI, the accessibility of the device in Tucker et al. [29] is limited since access to the GUI requires an intricate installation procedure.

In this paper, we describe the design of the SIPPC's graphical user interface (GUI) and its application of these design principles. Through the GUI, we can offer a fine-level of control of the therapy device such that the device can be used to support a larger set of patient needs and facilitate precision rehabilitation. We also present preliminary data from an ongoing study of infant locomotor learning.

Materials and System

Self-Initiated Prone Progression Crawler

The SIPPC 4 (Figure 2) is the latest generation in a series of integrated assistive crawling robotic systems that promotes prone locomotor learning in infants with motor delays [21]. The infant lies prone on a padded platform such that their hips, trunk and potentially their head are supported, while their hands, feet and knees are able to contact the floor. The SIPPC uses information from a set of sensors to assist the infant in motor training for precision rehabilitation. Embedded inside the platform is a 6-degrees-of-freedom force/torque (F/T) sensor with which ground reaction forces and weight shift can be measured. An infant motion capture suit tracks limb and trunk movements in real-time using twelve Inertial Measurement Units (IMUs) [32]. The 3D orientation data from the IMUs are combined with a skeletal model of the infant to estimate the 3D locations of key points on the infant's body, including the wrists, ankles, and feet [33]. Three cameras capture lateral views of the infant, the infant's head, hands and feet, as well as area in front of the infant. The images from the cameras are composited into a single view by a dedicated video processor; the composite image is recorde to disk and sent to the connected client devices (e.g., tablet, smartphone).

The SIPPC has two drive wheels mounted on either side of the infant's hips. Each wheel is independently controlled by a local microcontroller that communicates with the control processor, which is responsible for coordinating their behavior and monitoring their state for safety. A rear ball castor wheel sits behind the infant as a third point of contact and a front skid plate prevents the SIPPC from tipping. Flexible platform covers at the front of the platform and around the wheel pods prevent the infant's hands from being pinched when the robot moves. Additional details about the hardware design of the SIPPC are described by Ghazi et al. [34].

Software System Design The SIPPC software system is built on top of the Robot Operating System (ROS,

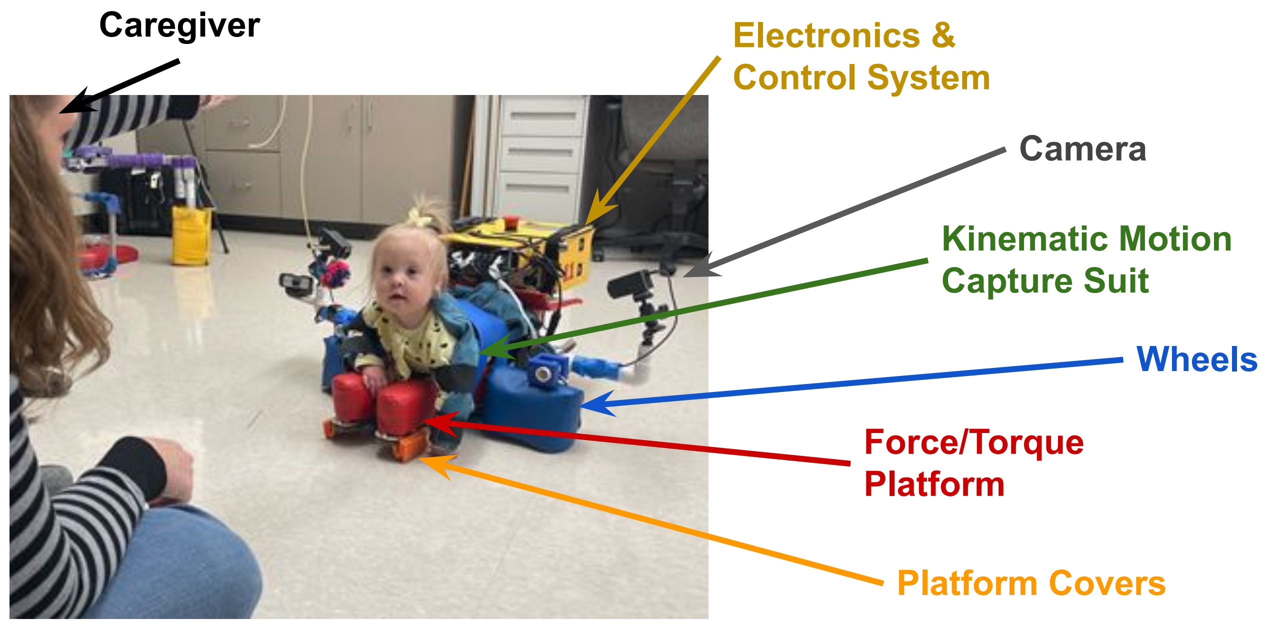

Figure 2: A therapy session where the infant is using the Self-Initiated Prone Progression Crawler (SIPPC 4). The parent is in front of the infant encouraging her to move her limbs and progress forward. The infant is outfitted with an eleven-segment motion capture suit. Three cameras record the limb movements and the space in front of the infant. Under the red platform, a force/torque sensor measures the ground reaction forces (GRFs) that she generates. The yellow box behind the infant is the electronics box housing most of the robot's processors, the battery, and the power regulation system.

v1, Kinetic Kame) [35], which supports the flexible, real-time communication and coordination between a large number of sensory, logging and control processes (referred to as ROS nodes). These ROS nodes are distributed across multpile processors and implemented with a mix of C++11 and Python. The base update rate for the real-time processes (including sensing, control and logging processes) is 50Hz. Event-based processes wait for a trigger event to perform an update, such as parameter change events from the GUI.

The software architecture details are outlined in Figure 4 and described by Ghazi et al. [34]. In short, the sensor nodes gather and publish data from the force/torque sensor, the motion capture suit, the SIPPC wheel state, the cameras, and the battery. A low-level control node is responsible for producing smooth and safe motions of the SIPPC. A video compositor node is responsible for the real-time integration of the images from three separate cameras and graphical representations of the SIPPC state into a single video stream, which is then transmitted to the GUI at 10FPS and recorded to disk for later coding. A session control node is responsible for enforcing the sequence of allowable steps that the therapist can take during a recording session. A logging node is responsible for writing all key SIPPC state information to a log file for later analysis. And, a processor node is responsible for monitoring the CPU load, memory, and data storage on each processor.

The GUI communicates through ROS to present the robot system state to the therapist and to enable the therapist to tune the robot responses to each infant's personal needs. The GUI receives regular robot and infant state updates through ROS at 10Hz. The therapist is also provided with diagnostic details for real-time troubleshooting should issues arise. ROSBridge [36] is a ROS package enabling communication between the ROS environment on the robot and the client devices (e.g., phone, tablet). The package uses WebSockets to transmit data in the JavaScript Object Notation (JSON) [37] format and maintain a shared robot state across all connected devices. The robot uses a RaspberryPi (RPi) [38] as an access point (AP) for client devices to

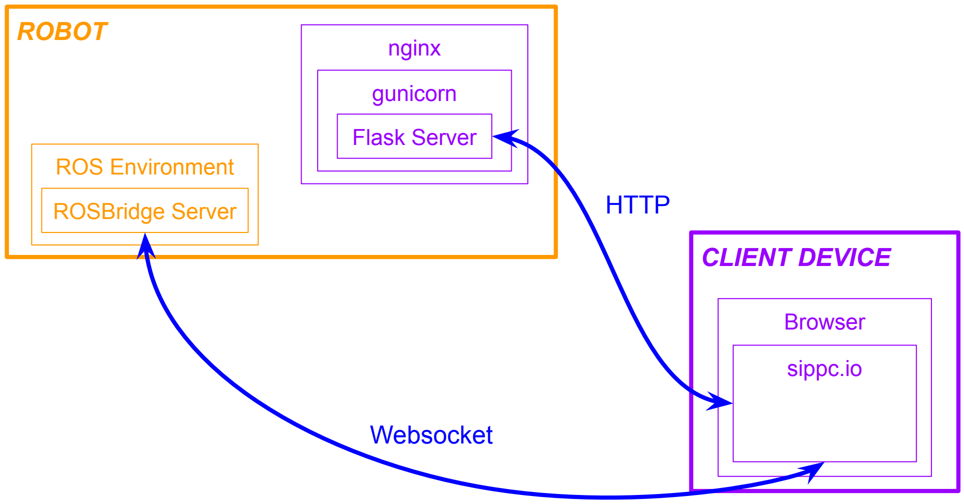

Figure 3: Web Architecture. Robot data flows between the ROS environment on the robot (using WebSockets) and client devices (e.g., phone, laptop, tablet). The Flask web server on the robot hosts and transmits the pages to the connected clients. State change requests flow between the Flask server on the robot and the client device and back to ROS to valid state change requests. The ROSBridge server carries the protocol for converting ROS messages into JavaScript Object Notation (JSON) for transport through the WebSocket.

connect to and a web server for users to access the various pages of the user interface. A high-level diagram of the web architecture is shown in Figure 3. The web application server uses Python Flask [39] to define the endpoints corresponding to each of the interface's pages. Each page provides information about the infant's progress, controls for monitoring the robot's state, or capabilities for managing the data. Guincorn [40] is a gateway server that manages multiple processes for handling client requests in parallel when multiple users are simultaneously connected to the interface. Nginx [41] acts as a reverse proxy server for port forwarding. For dynamic device layout adjustment, Bootstrap generates responsive styles that allow simple specifications for automatic layout rearrangement based on the size or resolution of the client's device.

Networking An outline of the network and device connections is shown in Figure 5. The robot has five specialized processors (three RaspberryPi's (RPi) and two Mbed microprocessors). These processors communicate on the same subnet via Ethernet. The main RPi (sippcbridge) acts as an access point and web server. Client devices (e.g., tablet) connect to sippcbridge to access the SIPPC's local password-protected WiFi network and the GUI. The main RPi also hosts the ROS master process, which manages the ROS nodes and the inter-node communication. The robot can be connected to the internet through the sippcbridge to synchronize data between the secure cloud storage, other SIPPC robots, and secure remote lab devices for software updates and maintenance. The video RPi (sippcvideo) is dedicated to capturing video from the cameras and compositing them into one video stream along with data plots of the kinematic and robot data. The solid state drive (SSD) for storing all the session data on the robot is connected to sippcvideo. The SSD is mounted by the other RPi's over the robot's local network. The control Mbed (sippccontrol) monitors and manipulates the wheels and force/torque (F/T) sensor. The suit Mbed is connected to the twelve IMUs and is responsible for collating and transmitting the 3D orientation data to other nodes in the network.

Robot Assistance Control Modes

Control modes are types of robot assistance that trigger responses by the robot based on actions that the infant performs. There are two general types of control modes the therapists can engage for the robot: proportional and discrete. For the force control mode, the robot acceleration is linearly related to the magnitude of the infant-generated GRFs. The gain of this relationship is a parameter that the therapist can adjust under the Force/Torque Control panel on the Parameter Page (Figure 7; Forward Force Boost and Turning Torque Boost parameters).

The discrete control modes produce temporally extended, minimum jerk trajectory profiles in the forward, left or right directions. Only one discrete action can be triggered at a time; its acceleration profile is layered on top of that of the force controller. The parameters of the profile (temporal duration and distance) can be altered by the therapist. Several different discrete control modes are available: power steering (PS), suit gesture recognition, and manual control. Assistance from PS is triggered when the GRFs exceed a threshold that the therapist defines. Two suit gesture control modes are available: Gesture 1 (G1) and Gesture 2 (G2). G1 is a heuristically defined set of rules that translate limb motion into triggering a discrete robot response [32]. G2 is a separate set of machine-learned (ML) gesture rules encoded with a forest of relational probability trees [42, 43]. This model was trained using kinematic and PS assistance event data from typically developing infants learning to use the SIPPC with PS only [21]. G2 identifies additional, more precise types of limb movements beyond what can visually be observed and defined by the therapists. G1 responds more to coarse-level movements in the arms and legs, whereas the sensitivity of G2 can be dynamically adjusted to encourage more coordinated crawling-like movements. Specifically, the G2 model produces as output an estimated probability of a forward, left or right movement. When one of these predictions exceeds a therapist-defined threshold, the G2 control mode generates the corresponding discrete movement. As a probability threshold increases, the infant must produce movements that better match the movements of the typically developing infants from the training set. These parameters are under Session Configuration: Gesture 2 Sensitivity on the Session View page (Figure 6). Finally, the Manual control mode allows the therapist to remotely drive the robot.

User Interface

The SIPPC GUI is used by the therapist to guide motor training by allowing the therapists to control the difficulty of the sessions, dynamically. The GUI allows the therapist to adjust the control parameters of the robot in real-time to modify its responsiveness based on the infant's engagement and movement. The therapist can modify multiple parameters as the infant becomes more skilled at driving the robot to ensure that the infant is continually challenged to practice and learn more difficult motor skills. Therapists can adjust parameters such as:

- GRF response threshold to adjust performance difficulty,
- limb and trunk gesture recognition sensitivity to adjust performance difficulty,
- robot control modes to target limb use for generating movement, and
- robot movement magnitude and duration to motivate limb and trunk movement.

Early on, when the infants are less skilled, the robot is configured to be very responsive. Sessions can be made less challenging for infants with more severe motor impairments or more encouraging for infants with less motivation to move. This allows infants to practice motor activities at their current skill level. For example, if the infant is visually engaged with a toy but not moving towards it, the therapist can make it easier for the infant to achieve success. The therapist can increase the gesture sensitivity to detect small limb movements of the infant to drive the robot toward the toy. Conversely, if the infant is easily generating robot movements by actively reaching, pushing, kicking, and progressing toward toys, the therapist can increase the challenge of driving the robot. This can be achieved with multiple combinations of changes to the robot parameters in the GUI. For example, the therapist can decrease the distance that the robot travels and increase the amount of force that the infant must generate to move toward the desired item.

The SIPPC GUI promotes the proposed design principles by being accessible by most personal devices (e.g., tablet, laptop, smartphone, etc.), maintaining a consistent shared state across all connected devices, being self-contained and informative, being modular in design, and limiting session procedural operations to a specified sequence. To meet these requirements, the GUI was built as a local web application. Web applications are accessible on any device with WiFi connection abilities and are hardware agnostic, eliminating the need to explicitly develop the interface for multiple types of devices. Additionally, web applications do not require installation on a client device and are accessed simply by connecting to the robot's local network and the SIPPC URL from a browser. For security, the robot and its local WiFi network are password protected. One must connect to the robot's network to access the GUI.

Most operations in the GUI are performed by pressing a single toggle button and changing parameters is done by selecting checkboxes or moving a slider. Additionally, the interactive components of the interface (e.g., buttons) change appearance if interacted with correctly, to clearly indicate to the users the button's current state. This simplifies the interface and the workflow for the therapists. For example, the toggle buttons change color and text to indicate state information. In particular, the button to start and stop Data Recording is red and displays "STOPPED" when data recording is not running. When data recording is running, the color changes to yellow and the text inside the button is set to "STARTED." The sliders display the value for their corresponding parameter in a text box that the user can use to type the value instead if typing is preferred to using the slider.

Multiple client devices can be connected to the GUI of the same robot simultaneously to observe the system state. To ensure a consistent state across the connected devices, each device receives the state data from a centralized parameter ROS node; any parameter changes from the therapist are sent as change requests to this node, which validates the change before altering the system state. The ability to have multiple client devices connected to the robot's interface also assists therapists with training others to use the system, involving the infant's caregivers and monitoring safety information. The user interface is separated into eight pages (Session View, Parameter Page, Post Processing, Subject Page, Clinician Page, User Guide, System Details, and Admin Dashboard; Figure 6 and 7). Each page focuses on specific therapist tasks. Troubleshooting details and a user guide are included in the interface for convenience to clarify how various interface tools operate and to explain the causes and solutions to issues that might arise while users are interacting with the SIPPC.

Session View The main interface page is the Session View (Figure 6). This page displays the robot and sensor status information (e.g., whether the force sensors are connected), and allows the therapist to engage/disengage the robot, drive the robot (i.e., Manual Assist panel in Figure 6), perform suit calibration for the trunk and limbs (Suit Calibration panel in Figure 6), modify the session configuration (i.e., robot-infant interaction parameters), and control the trial state (e.g., start or pause the trial timer). The therapist can also take notes that are logged along with other system data for use during subsequent sessions and analyses.

The panels on the page also facilitate modularity in the interface design. The panels are automatically rearranged for different screen resolutions and are laid out in an order that reflects the typical temporal order of the activities taken by a therapist during a session/trial. The interface will not allow certain actions to be performed before others. If the user requests an invalid sequence the interface notifies the user of the issue and the correct action to perform. For example, before Data Recording can start, the connection to the wheels, force/torque sensors, and other processors must be established (System Status panel in Figure 6, each indicated by a green check mark), and the subject and clinician must be selected. Precautionary checks are built into the

SIPPC. The robot cannot be engaged without the wheels and force sensors being connected. Before starting the first trial, the suit must be connected and the suit and the Force/Torque Sensor must be calibrated. Therapists can start the trial and engage the robot and the infant's control when all precautions are met. This design reduces errors in the procedures and promotes consistency across sessions, subjects, and therapists. The checks in the system also reduce the chances of erroneous interactions with the robot that could result in damaged or missing data.

Parameters Configuration The Parameters Page (Figure 7) exposes robot-infant interaction parameters, allowing in-session adjustments. Modifications to these parameters enable the therapists to guide motor training on an individual basis. These configurations can be saved and shared across multiple robots on an individual basis. The Discrete Assistance panel modifies the parameters impacting the robot's response to assistance events triggered by the power steering or gesture recognition control modes. The Power Steering panel allows therapists to adjust the threshold GRFs necessary to provide the infant with extra force-based assistance to move forward, left, or right. The lower the threshold, the easier it is to trigger a power-steering-assisted boost. Force/Torque Sensor parameters manage the filtering of sensor noise. The Force/Torque Control parameters handle the robot's level of continuous response to the infant's GRFs (the Global Gain and Boost parameters). Increasing the Boost parameters increases the robot's acceleration proportional to the GRFs and can provide infants with extra motivation in response to smaller forces when the infant might be struggling to produce forces. Lastly, the damping parameters control how quickly the robot slows down after a movement has been completed.

Data Handling The Post-Processing page (Figure S1), guides users through the steps for data post-processing, uploading, and deletion. The structure and functionality of the page restrict the order in which the steps can be performed to prevent loss of data and minimize the time and effort spent on data management. For example, video data cannot be uploaded until after it is compressed. Files cannot be deleted until after they have been uploaded. Therapists can also download subject parameter configuration files and notes from other robots and sessions to use for current sessions, allowing the different robots to be interchangeably used for therapy sessions. All data are uploaded to the HIPAA-compliant version of Box. Only authorized users can access this data repository. All data exchanges with Box are encrypted in transit, and Box encrypts the data at rest. Post-processing is done on a computing system at the University of Oklahoma (OU) where the data are stored on a ZFS-based system with encrypted disks and three parity disks to prevent data loss. Data exchanges between this file system and the processing computers are also encrypted in transit. Data (including video) are stored on the SIPPC until the videos can be transmitted, processed, and human-verified (typically takes one week). See the Supplemental Details for details on all the pages in the GUI.

Methods

Design Requirements

The current SIPPC robot and interface evolved from prior studies involving the SIPPC 2 [21, 22, 44] and SIPPC 3 [23, 27]. SIPPC 2 was the first functional prototype to be used in a study that allowed for the comparison of typically developing and at risk infants. The robot passively accelerated in response to GRFs, but the control system could also generate short duration acceleration "bumps" in response to small passively-generated movements (similar to PS) and to gesture recognition events (G1, specifically). The

Goal	Requirement	GUI Page
Facilitate personalization of therapy and monitoring	Select infant and clinician profiles	Session View
	Start/stop data recording sessions	
	Start/pause/resume/stop trials within each data collection session	
	Calibrate the suit and force/torque sensors	
	View infant performance and robot behaviors	
	Control robot response and behavior (i.e., ability to change control parameters)	
Facilitate monitoring	View robot system state and details (e.g., battery, sensor states, processor load and memory, data storage space, etc)	Session View and System Details
	Provide real-time troubleshooting information and robot and GUI documentation	All and User Guide
	Enforce compliance with the study procedures and protocol	All Pages
	Accessible from network-enabled devices (e.g., phone, tablet, laptop, etc)	
Data Management	Share infant profile data between robots such that they are interchangeable	Post-Processing
	Manage data (upload, download, delete)	
	Shut down robot	System Details

Table 1: GUI Design Requirements

wire-connected interface computer provided the therapist with minimal abilities to start/stop trial recording to visualize the state of a small battery of sensors. SIPPC 3 expanded the sensory and motor capabilities of the system, allowing for higher fidelity data collection and the ability to prototype additional movement contingencies, including PS, G1 and G2. The GUI executed on a wireless laptop computer, and allowed the therapist to select control modes and adjust a small number of control parameters. However, following the prototype phase, these parameters were fixed for the purposes of the subsequent study that compared typically developing infants with at risk infants.

SIPPC 4, the subject of this paper, is part of a larger study that is focused on providing personalized motor training to the infants using fine-level dosage control [45]. The new requirements for this therapy-focused study include: a flexible interface that is accessible from any WiFI-enabled device, and GUI-based real-time, fine-level control over the device responses, as well as the data management processes. A key challenge in allowing the therapists to have fine-level control of the SIPPC behavior was in balancing this complexity with their need to focus on the infant during the therapy sessions. Table 1 summarizes the specific requirements to achieve these goals.

Validation and Testing

Prior versions of the SIPPC allowed us to prototype a range of ideas for supporting infant crawling learning and infant-robot interaction. The SIPPC 4 represents a consolidation of these efforts into a device that is practical for use in homes and flexible enough to allow for a wide range of infant-robot interaction profiles. The current GUI and SIPPC 4 robot were tested with 4 infants between the ages of 5 and 9 months, by two therapists over five months at OU Health Sciences Center before deployment to CHOP (the Children's Hospital of Philadelphia) for the clinical study. The test sessions with the infants were conducted using the same clinical study procedures outlined in Prosser et al. [45]. Test sessions consisted of three 5-minute trials of active motor training. Infants were outfitted with the motion capture suit, placed on the SIPPC, and encouraged to move toward toys by the therapists. The therapists tested the data recording, trial control, robot and parameter control, video streaming, sensor calibration, data management, note-taking, robot state display, and infant profile management operations of the GUI. After each testing session, the therapists provided the engineering team with feedback about their experience, including the functionality and ease of use of the GUI and the expected functionality of the SIPPC. This feedback led to adjustments to the organization and operation of the GUI components. In particular, the order of GUI components in the interface was changed to reflect the temporal order in which the therapists tended to interact with these different components. In addition, we adjusted the range of selectable control parameter values to better reflect the useful range of values, as perceived by the therapists.

The GUI is also robust to different operating systems (OSs) since web applications are designed to be browser-based and thus largely hardware and OS agnostic. The GUI was tested on Linux, Windows, Andriod, iPhones, and iPads. The GUI layout and styles dynamically changed to accommodate different screen sizes and resolutions for various devices such as phones and laptops. The GUI was also tested using the Edge, Chrome, Safari, and Firefox web browsers and operated similarly during the sessions in each.

Data Collection Protocol

The SIPPC 4 is one of three stages in a larger, ongoing study on locomotor development of infants at high risk for CP [45]. The first stage is Early Spontaneous Neuromotor Behavior, the second stage is Prone Locomotor Training with the SIPPC, and the third stage is Upright Locomotor Training. The larger study will enroll 60 infants. Presently, over 30 infants have participated in the prone stage. The inclusion criteria for the infants in the larger research study are a brain injury at birth without other known genetic conditions unrelated to CP. Infants are considered to be at high risk for CP if they have Absent Fidgety movements on the General Movements Assessment at 3 or 4 months of age [46] and/or score below the 16th percentile on the Test of Infant Motor Performance (TIMP) Scales [47] at 4 months of age.

For the second stage of the study with the SIPPC, infants participate in prone training sessions, with each therapy session ideally consisting of three trials (in practice, the number of trials depends on the disposition of the infant). Active training time during each trial is 5 minutes [45]. Sessions are conducted three times a week starting when the infant is 5 months of age until the infant is 9 months of age (ages are corrected if the infant is born before 37 weeks) or until the infant begins to crawl independently. Prone training sessions occur at the infant's home, at their inpatient bedside, or in a Center for Rehabilitation outpatient location (i.e., CHOP), depending on the most convenient location for the family. Currently data collection is ongoing. Further details on the participants and the study protocol are in [45].

For each therapy session, the therapist work with the caregiver to use time with the infant as effecitvely as possible. After powering on the SIPPC, a period of four minutes is required to ensure all components are booted and initialized. During this time, the motion capture suit is placed onto the infant before placing and securing the infant prone onto the platform. Additionally, the therapist open the Session View page of the GUI (Figure 6) to verify that all the sensors are connected. Once the SIPPC is ready, the Session View page is used to set up and control the SIPPC to guide motor training. The appropriate infant profile is selected based on the infant code number (prefix "LL0") from a drop-down menu on the Session View page. Before each trial, the suit and force/torque (F/T) sensors are calibrated by pressing the corresponding buttons in the GUI. The initial calibration of these sensors is paramount to the protocol and thus must be completed before trials may be initiated. While the IMUs are strapped to the infant, their orientation relative to the joints is unknown. These orientation offsets are measured by placing the infant into a known configuration, with both arms extended to 90 degrees of abduction (to form a 'T'), the trunk horizontal, and the legs straight with the feet plantarflexed. As each segment is positioned, the therapist presses the corresponding calibration button (Figure 6). The F/T sensor is calibrated by pressing the "Force/Torque Calibration" button in the GUI (Figure 6), to tare out the infant's weight and mass distribution.

The therapist then checks the three camera views in the GUI's video stream to verify that they capture all the infant's limbs and the objects in front of the infant. The robot response and infant control are engaged before starting the trial timer by using the corresponding buttons in the Trial Control panel of the Session View page (Figure 6). The trial timer will automatically stop once 5 minutes of active prone training has elapsed. The therapist can also pause and resume the trial timer, as needed, to turn the SIPPC away from obstacles or untangle any cabling or hoses that are connected to the infant (these connections are not related to the study). During each trial, the infant is encouraged by the therapist or caregivers to move toward motivating objects (e.g., toys, teethers, or caregivers) and practice lifting their head, shifting weight, reaching, kicking, and other crawling-relevant movements. During these sessions, the therapist uses the GUI (typically the Session View or Parameter Page; Figure 7) for any additional modifications to the robot responsiveness in real-time, based on the infant's performance, skill level, mood, environment, or unique needs for practicing and promoting locomotion.

Results: Therapists-Robot-Infant Interaction

Most data flowing through the SIPPC system are logged for the entire duration of the data collection session; each element of data is time-stamped at a millisecond resolution. Logging commences once the therapist provides key session data, including subject and therapist ID, and continues through all session trials. The logged data include robot state, infant kinematics, all GUI input events, and any response that the system has to these requests from the therapist. This information allows us to assess how the therapist is using the GUI within individual sessions and longitudinally across the full set of sessions. For example, we can measure 1) the frequency at which the therapist makes adjustments to the SIPPC control parameters and when these changes are made (specifically, preceding a trial vs during a trial; Figures 8–10), 2) the frequency of minor procedural deviations for situations in which the therapist has some latitude in deciding when or whether to perform certain activities (e.g., whether the suit is re-calibrated between trials; Figure 10), 3) longitudinal changes in the use of the different control modes and associated parameters (Figures 8–11), and 4) the number and degree of completion of each trial within a session.

Usability

The therapists (and sometimes caregivers) were the main users of the GUI. The therapists report that the GUI operated correctly during most sessions. The therapists describe the infants as demonstrating a wide range of motor skills and motivation to move at the start of SIPPC therapy sessions. The therapists report changing the parameters over time to adapt to the infants and their changes when appropriate. Generally, the therapist sets the GRF threshold low in the initial training sessions. This causes more frequent robot movements in response to any movement initiated by the infant, including random weight shifts and spontaneous extremity movements. The discrete movement distance parameter was also set high so that the robot could travel to desired items with few steps.

With time, many infants demonstrated more consistent, coordinated movements (e.g., reaching, head lifting, kicking and weight shifting) to move the robot, indicating that the infant was learning how to use their intentional movements to move in the environment. In response, the therapists adjusted the parameters to make it more challenging for the infant by increasing the GRF threshold and decreasing the distance that the robot travels. The infant then had to produce larger forces and move more to reach desired items in the environment.

For some infants, initial interactions with the SIPPC, or being prone, required the therapist to use an alternative approach. An example from the therapist's experience is one infant who did not tolerate being prone on the platform and had very limited tolerance to being prone off of the SIPPC. On the SIPPC, this resulted in increased weight shifts, limb movements, and changes in GRFs. The SIPPC's response to these movements and GRF changes was forward motion that further upset the infant. For this infant, being on the SIPPC was unpredictable and resulted in the infant being unable to achieve a calm state for engaging in the training session. Therefore, the treatment goal for this infant began with increasing tolerance for prone positioning on the SIPPC by decreasing movement of the robot. The therapists used the GUI to reduce the robot's response by decreasing the forward distance the robot traveled in response to the infant's movement and to increase the GRF threshold required to move the robot. The gesture recognition modes for the suit were also turned off to reduce the likelihood of unintended robot movements in response to limb movements. This dampened the SIPPC's responses such that if the infant produced spontaneous limb movements, it resulted in minimal response from the SIPPC, creating a more stable and predictable play environment for the infant. As the infant's tolerance for prone positioning improved, the infant was able to be on the SIPPC while remaining calm engaging in play. Then, the therapist was able to adjust the robot parameters to gradually increase the responsiveness of the SIPPC. By the end of the intervention time, the infant was able to tolerate prone positioning for all three trials, but was not able to produce much movement within his environment. Although this infant did not achieve proficiency with moving the SIPPC to interact with the environment by the end of the 16 weeks of training, the system was able to be modified to meet the individual needs and current skill set of the infant and gradually advanced as this skill set improved.

In general, the therapists report that the GUI performed consistently across therapy sessions. However, one common critique among the therapists is the inconvenience of scrolling between the video stream and main session operations on the Session View page while working with the infant. One therapist would zoom out on the page to include more components within a single view. Overall, the therapists reported that major issues were rare and found the GUI easy to use and intuitive once they had been trained to use the system.

When preparing the SIPPC for a therapy session the therapists report needing to spend 5–10 minutes in both the home and inpatient settings. Calibrating the suit took less than 30 seconds. In addition, the therapists often checked the data streams and sensor status to verify proper functioning of the full system. Latencies in these streams are on the order of 10s to 100 ms and are generally not perceived by the therapist. The GUI is configured to receive robot and infant data at 10Hz, with the video stream averaging 8 to 9FPS during live therapy sessions. In some error conditions (e.g., low data storage space, loose sensor connections), detailed diagnostic information from the GUI was sufficient for the therapist to resolve the problem. In other instances, the therapists would have to restart the system, delaying the start of the session. On rare occasions, some issues such as an interfering WiFi access point or a mechanical failure could not be solved in the field by the therapist.

Preliminary Data

In Figures 8, 9, and 10, we illustrate the data that is being captured, present examples of how the therapist uses the GUI, and describe how the therapist changes to control system parameters relate to infant activity. An overview of concurrent infant, robot, and GUI parameter data during a single trial for the infant with the subject code LL011 is shown in Figure 8. A subset of the parameter values and their changes are shown under Therapist Controls in the figure. The times when the infant triggers a discrete assistance and the type (indicated by color), are shown under Robot Assistance. The changes in the robot velocities and detected forces are under Robot State. The speed of the infant's wrists and ankles and the head height are under Infant Kinematics.

In the GUI, therapists can pause trials to temporarily disable the infant's control of the robot to manually drive the robot and reposition it when the infant runs out of forward-moving space. The first row, labeled as Trial Paused, has red patches indicating the duration and times when the therapists pause the trial (the pause button is found under the Trial Control panel in Figure 6). Under Therapist Controls, in the rows corresponding to Assistive Movement Linear Distance, PS Linear Threshold, and PS Rotational Threshold, we see the values of several control mode parameters that therapists can change to adjust the robot sensitivity. Assistive Linear Distance corresponds to the Distance parameter under Discrete Assistance on the SIPPC Parameters page (Figure 7). Decreasing the distance parameter reduces how far the SIPPC will travel after a discrete assist (e.g., power steering) is triggered by the infant. The therapist increases the Power steering (PS) Linear Threshold twice, making triggering PS assistance more challenging for the infant. The red bars under Robot Assistance indicate that the infant generated enough GRF to trigger PS assistance. The peaks in GRFs (i.e., Forward Force and Turning Torque) can be observed whenever PS is triggered. The light-blue box starts slightly after 100s. A few seconds before this time frame, the infant triggers left movements using Gesture 1 (G1) assistance, followed by forward movements using PS. These are indicated by the blue bars and the following red bars, respectively, under the Robot Assistance section. Under the Robot State section, there is a corresponding positive peak in the rotational robot velocity that occurs just before the left G1 events. Following the left G1 events are the forward PS events, that correspond to a positive square peak in linear robot velocity under the Robot State section. Then, the trial is paused as indicated by the red patches under the Therapist Controls for Trial Paused. After the trial is paused, the therapist manually drives the robot backward and then to the right, as seen by the black bars in the Robot Assistance section. Under the Robot State section, there are small corresponding negative peaks in the linear robot velocity when moving the robot backward and negative peaks in the rotational robot velocity when turning the robot to the right (at around 150s). G1 is triggered by infant limb gestures, therefore, we see peaks in the limb speeds under Infant Kinematics. However, due to the complexity of gestures that trigger robot assistance events, it is difficult from just the limb speeds to describe the precise gesture that caused the assistance event. Another interesting observation from this figure is the head height under the Infant Kinematics section. The head height was relatively constant then started increasing sometime before 100s. The peaks indicate the infant was moving their head up and down. Then before 200s, the head height appears to stabilize.

Four example trials for one subject (infant LL013) at different weeks in the study are shown in Figure 9. In particular, it shows longitudinal changes in infant activity, changes in how the infant engages with the SIPPC, and active changes the therapist is making to the control system parameters during the trials. These observations are also supported by Tables 2a and 2b. During weeks 4 and 8 fewer overall Robot Assistance events are triggered than in weeks 12 and 16. The number of PS (red) to G1 (blue) infant-triggered assistance events is about the same in weeks 4 and 8 (Tables 2a and 2b). In weeks 12 and 16, G1 is triggered at least twice as often as PS. The average assistance counts over 4-week periods are shown in Table 2b. A linear model is fit to the 4-week averages in Table 2b and the coefficient of determination (R^2) and its corresponding p-value are computed to identify increases in the use of the robot assistance as the infant matures. There is a significant increase in the average number of G1 events throughout the study ($p < 0.008$). There is no strong trend in the average number of PS events ($p < 0.574$). The average number of PS events increases in the middle of the study and then drops in the last four weeks. Additionally, we observe changes in how the therapist modifies the parameters over time. In week 4, the therapist adjusts parameters multiple times throughout the trial. In week 8, the therapist adjusts the parameters once in the middle of the trial. In weeks 12 and 16, the therapist adjusts the parameters within the first 100s of the trial. Lastly, most of the infant-triggered robot assistance events are in the forward direction and the number of events increases from weeks 4 and 8 to weeks 12 and 16.

Figure 10, along with Figure 11, illustrate the high-level control mode choices that the therapists are making longitudinally and their potential impact on assistance events across the infants. As part of the therapy standard procedure, therapists calibrate the suit (blue) at the beginning of each trial, though is not required so as to give the therapist flexibility in working with the infant. Out of 1382 trials, the suit is calibrated for 89% of them.

Therapists also have the option to write notes (Session Notes; orange) in the GUI during trials. This feature is used on average for 72% of the trials for most infants. Additionally, the therapists used the GUI to enable the control modes Power Steering (PS; green) and G1 (Gesture 1; red) during most trials (99% and 85% of the trials, respectively). In particular, the trials where each control mode is enabled for more than 50% of the trial duration, are seen in Figure 10. G2 (Gesture 2; purple) is typically enabled when G1 is turned off, such as in weeks 4 through 12 for infant LL041. G2 is typically unused during trials early in the study because G2 requires more precise movements to be triggered; exceptions are infants LL006 and LL015. Generally, G2 is enabled in trials later in the study, such as for infants LL016 and LL028. For infants, LL040-LL042, the therapists enabled G2 for at least half of the weeks in the study. In Figure 11 are the 4-week averages of the assistance counts across infants. As expected, infants who have G2 enabled for a consistent time frame have non-zero average event counts during one or more 4-week periods. G1 appears to have the most counts more often than PS. However, these counts are also impacted by therapist decisions for parameters such as the PS thresholds. Figures 9 and 11, and Table 2 are consistent with the observation for infant LL013 that the PS is triggered less than G1. Increases in PS thresholds seen in Figure 9 suggest the influence of these parameters on potentially favoring G1 over PS, since increasing PS thresholds makes triggering PS more challenging. A more detailed analysis comparing kinematics, GRFs, assistance counts, and robot behavior with the therapist's chosen parameter values will provide further insight into the infant behavior and development. It will be discussed more in future work.

Infant LL013	Power Steering	Gesture 1
Week 4	13	11
Week 8	10	15
Week 12	16	32
Week 16	8	32

(a) Discrete assistance counts for trials in Figure 9

Infant LL013	Power Steering	Gesture 1
Week 1 to 4	7.2	15.9
Week 5 to 8	9.1	20.3
Week 9 to 12	9.9	25.7
Week 13 to 16	4.1	33.2
R^2	0.1815	0.9841
p-value	0.574	0.008

(b) 4-week averages of the discrete assistance counts for infant LL013

Table 2: Example of 4-week assistance count data. (a) lists the total number of Power steering (PS) and gesture 1 (G1) events for each trial in Figure 9, and (b) lists the 4-week averages of the number of discrete assistance events for infant LL013. This can provide a general understanding of changes in infant engagement with the discrete assistance events in an environment where the therapist's parameter decisions also affect the counts. A linear model is fit to the average assistance counts to compute the strength of the relationship between the week in the study and the assistance counts. This is indicated by R^2 (coefficient of determination) and the corresponding p-value. This is an example of one type of analysis that can be performed to understand and summarize longitudinal patterns for each infant.

Discussion

Infants at high risk for CP often have limited opportunities to experience movement than their peers and many do not learn independent prone locomotion skills. The development of the SIPPC 4 assistive crawling robot was guided by prior versions [21–23, 27, 44] and our proposed design principles. The current version of the GUI augments and expands upon the contributions of the prior SIPPC studies. Based on preliminary data and feedback from the therapists, the GUI facilitates personalized motor training opportunities for infants at risk of CP and with motor delays. Prone training on the SIPPC, in conjunction with guidance from the therapists using the GUI, provides infants with CP with more opportunities to practice prone skills that will encourage locomotion (e.g., head lifting, weight bearing on the arms, and reaching) while teaching the infants that purposefully initiated actions can result in successful movement towards a desired goal. Using the GUI to adjust the feedback also offers an intuitive method of communication with the learner, particularly when communication challenges are present (e.g., with infants).

The GUI provides an approach for data monitoring and documentation to observe therapist-robot-infant interaction and infant performance (Figures 8–12). The unique design of the SIPPC GUI as a web application makes it uniquely available to all authorized users with any WiFi-enabled devices (e.g., laptop, tablet, phone) in their favorite browser. No special installations or configurations are required for therapists or caregivers to easily access the GUI to monitor infant and robot behavior or modify the therapy. The GUI design also makes it easy for authorized users to share data and parameter configurations with post-processing systems or between other SIPPC robots, all from the same interface.

From Figure 9 and Tables 2a and 2b, Infant LL013 showed an increase in Gesture 1 (G1) movements, suggesting potential improvements in limb movement generation and coordination, as well as influences from the therapist's parameter decisions. The Power steering (PS) thresholds may be high enough such that G1 assistance events are more likely to trigger instead (since only one discrete movement may be triggered at one time). Data available through the GUI provides the potential to monitor longitudinal changes in locomotor behavior, skill, and their relationship to actions taken by therapists to guide motor training. A variety of control modes (Session Configuration section in Figures 6 and 10), with variable levels of assistance

(Parameters in Figures 7 and 8), are available for adjustment by the therapist in the GUI. The control modes and assistance levels allow infants at any developmental stage and motor level to explore and practice actions that are precursors to crawling (design principle 1). For example, the infant who the therapists reported initially did not tolerate being prone. The therapists were able to change the parameters in the GUI and modify the robot response such that the infant could acclimate to being prone and on the SIPPC. From Figure 10, although we observe the therapists enable PS more often than G1 for most sessions (99% and 85% of trials, respectively), we often see more G1 assistance events in many infants. This further implicates the need to analyze therapist treatment decisions with infant performance and robot response. This will allow us to quantitatively describe infant-specific choices therapists make. Such analyses will be performed in future work after completion of data collection.

From Figure 10, there are some consistent aspects of the therapy implementation, such as an adherence to the suit calibration before most trials. For approximately 89% of trials, the suit is calibrated before beginning subsequent trials. The GUI only mandates the suit calibration for the first trial at the start of the session and provides flexibility in calibrating subsequent trials for therapists to accommodate unique infant needs. In addition to suit calibration, the therapists choose to enable PS and G1 most of the time and consistently disable G2 early in the study for most infants. If G2 provides a useful training strategy early on for an infant, such as LL041 and LL042, then the therapists continue using G2 throughout most or all of the remainder of the study. Since the robots can share subject parameter configurations, this can easily be communicated to all therapists conducting therapy sessions for a particular infant.

Motivated by design principle two, the robot acts as a mediator from performance to results. The robot measures the infant's real-time performance using the kinematics and GRFs, and augments the infant's actions to encourage continued motor exploration. The infant performance relative to the robot response can be seen in Figures 8 and 9. We can identify when the robot moves and which limbs contribute to the movement. For example, in Figure 8, around 0s, a left robot movement is triggered due to G1 (blue bars under Robot Assistance). The peaks in the Right Wrist Speed and the Left Foot Speed suggest they are the likely contributors to triggering the assistance from G1. There is also a peak in the Robot Rotational Velocity, which is a left turn of the robot. At around 100s, peaks in the forward force trigger power steering and a forward robot movement. Most of the limbs likely contributed to the generation of this net force since multiple and frequent changes in limb speeds are observed under the Infant Kinematics. Additionally, in this particular trial, the right foot sensor was not collecting data due to a damaged cable. However, the SIPPC and GUI still operate functionally for therapeutic purposes since the SIPPC has control modes that are independent of the suit (i.e., Force Control and Power Steering). This suggests that multiple control strategies defined by different performance measures (e.g., force vs gesture) can be an approach to help enhance robustness to failure in clinical settings and reduce the likelihood of missed or failed sessions.

In Figure 9, we observe potential longitudinal behavioral changes in an infant LL013 as the changes in forces and limb speeds. We also see changes in the relative adjustments made by the therapists to the robot parameters (e.g., changes in PS thresholds). From the first 4 weeks to the last 4 weeks, the infant is triggering the robot assistance more frequently on average (Table 2b). G1 is triggered relatively more than PS in the later weeks. This might be due to changes in the limb movement and coordination relative to changes in strength to generate GRFs. However, this will also be impacted by the PS Thresholds. For example, the PS Linear Threshold is increased by the therapist near the beginning of the trials in weeks 12 and 16, whereas, the threshold is increased later in the trials in weeks 4 and 8. This increase in the PS threshold makes it more challenging to trigger PS and potentially increases the likelihood for G1 to be triggered instead since only one discrete assistance can be triggered at a time. This behavior could be ideal when an infant has met sufficient strength goals and the therapist wants to encourage the generation of more coordinated limb movements.

Moreover, the real-time robot response adjustment capabilities provided through the GUI make it possible for the therapists to help address real-time changes in infant mood and behavior as well as longitudinal changes in motor skills. For instance, from the therapist reports in the Usability Section, therapists can support infants who are initially responsive to therapy and infants who initially don't respond well to various aspects of prone training. The therapists were able to provide and progressively increase the challenge of the therapy session for the infants that were open to being on the SIPPC. As these infants became advanced in generating goal-directed robot movements (e.g., continuous movement towards toys), the therapist can immediately reduce the sensitivity of the robot response by either removing the suit recognition modes, increasing the GRF threshold for PS, or reducing the distance that the robot travels in response to infant movements. In situations where infants are uncomfortable on the SIPPC, the therapists also reported being able to guide these infants toward obtainable motor and behavioral goals. This was typically done by reducing the sensitivity of the robot to avoid upsetting the infant. This was done by disabling the gesture recognition modes and reducing the distance the robot moves. Once the infant became comfortable on the SIPPC, these control parameters were gradually and slowly restored to typical starting values.

Consistent with design principle three, the SIPPC GUI provides the therapist with detailed feedback (Figures 6, 8–12) that can be used dynamically to modify the behavior of the robot to further guide locomotor learning. By adjusting the robot behavior, motor training difficulty can either be decreased to motivate the infant or increased to challenge the infant. The ability to adjust the difficulty is crucial to prevent dependency on the robot-assistance, ensure that progress translates to daily life [4, 16] and is necessary to provide personalized care for precision rehabilitation [19]. This approach can provide the infants with more opportunities to move within their abilities and skill level while also allowing them to practice increasingly difficult actions.

Limitations

While many useful outcomes have been observed with the current application of the SIPPC-GUI system, some challenges have also been encountered. The current analyses are limited quantitatively because data collection is still ongoing. In future work, the complete analysis will compare all data from the SIPPC-GUI system (i.e., robot velocities, robot forces, robot parameters, infant kinematics, force, and video data, and GUI events). Presently, we describe the GUI design, its behavior and function, and a detailed qualitative analysis of the preliminary data to lay the groundwork for a more comprehensive analysis that will be done as future work.

Another challenge is the 4–5 minutes start up time for the robot and GUI to finish booting and initializing all components. This is particularly problematic as some infants have limited tolerance for waiting for a therapy session to start. Because of the interplay between the large number of hardware and software components, there exist substantial constraints on this boot-up sequence. Current timing was selected conservatively to ensure that all these timing dependencies were met. This full boot-up process will be evaluated in future work as the current version of the robot is mainly for research use.

Additionally, when therapists pause the infant's control to manually drive the robot, there are some instances when the infant is still performing an action. An example of this can be seen in Figure 8 after 100s. The infant is still moving the limbs at similar speeds while the therapist has paused the trial. Due to the trial pause, this action will have no impact on the robot response, even for intentional movements. Therefore, these pauses should be as short as possible, especially when the infant becomes more skilled.

Another limitation of the system is related to the camera view alignment. Camera alignment is not automatic and must be adjusted manually by the therapist such that the infant's limbs are clearly visible in the video feed shown in the GUI. Failing to take this step can negatively impact the human-driven analysis of the infant-robot behavior. Future system components could automatically analyze the incoming images and confirm that the alignment is sufficient.

The system can also be impacted by certain physical attributes of the therapy environment. In particular, certain flooring, such as some tiles and carpets, can alter the mobility of the robot, whereas infants might have little issue crawling over these same flooring conditions. Therefore, the parameter settings might need to be adjusted more often early in a session to improve the robot response to the flooring. The last limitation of the system is that the GUI presents a fixed organization of the graphical components. Future work could allow the therapists to customize the layout of Session View to make their interaction with the GUI more efficient and specific to their particular style of interaction.

Clinical Implications

The SIPPC offers a flexible and transportable system to adapt to the unique developmental path of each infant. It is crucial to provide rehabilitation that meets the individual needs of each infant. The design principles we have proposed in conjunction with the SIPPC and its GUI enable therapists to customize therapy contingent upon the specific needs of the learner and adjust the motor training difficulty to the unique skill level of each individual. In particular, infants with CP can face various combinations of challenges such as reduced strength, endurance, or coordination. The selection and configuration of GRF-based control modes such as PS, can address strength and endurance training. The gesture-based control modes (G1 and G2) can support infants who struggle with coordination or strength. Moreover, the combination of these types of control modes can target all these challenges for an infant who needs practice with each of them. The GUI is a valuable tool in providing a unique and individually tailored training program while utilizing the same general intervention approach for a variety of infant skill levels.

When providing intervention to facilitate developmental skill acquisition, it is important to provide a training environment that includes skill specificity, motivation for the infant, and modulated activity appropriate to the current skill level [7, 13, 21]. Using the GUI with SIPPC training allows for all of these conditions to be met and applies to a variety of infants. The SIPPC allows for crawling-like movements to result in forward motion toward desired toys (Figure 12). The GUI allows the activity to be easily and efficiently upgraded or downgraded to meet an appropriate training intensity for each infant (Figures 6–10). This feature is particularly important to tap into motor learning principles for developmental skill progression and precision rehabilitation. The activity needs to be challenging enough to continue to entice the infant into performing new and increasingly difficult skills, without being too challenging and resulting in decreased motivation for task performance.

Future Work

Future work will aim to improve the therapist's interaction with the robot through the GUI. Improving the boot-up speed of the SIPPC and GUI can further optimize time spent in motor training with infants. Additionally, wider angle video feeds or automated positional control of the cameras in the GUI can further increase the time that infants spend in motor training with the guidance of the therapist. However, the cameras are predominately for research use and not for pure clinical applications. The large amount of data available in the GUI can be overwhelming, therefore the ability of the therapists to quickly and easily customize the data presented in the GUI can further improve the quality of prone locomotor training for infants.

Future quantitative longitudinal analyses of the concurrent infant, robot, and parameter session data will be used to measure the design performance. For example, coders evaluate infant behavior and motor skills from the video collected during the sessions. These data will be compared with robot and parameter data to assess how therapist control changes impact infant locomotor behavior.

Future work should also apply these design principles to other assistive therapy devices, age groups, and motor disorders. The general design and layout of the GUI, and overall SIPPC system, can be adapted to other groups and devices such as robotic assistive gait devices. In the current system, user actions in the GUI send change requests to the robot control system. This same workflow can be applied to the corresponding control system of any robotic device and provide therapists with detailed control over the behavior of the robotic therapy device. Additionally, ROS is used to manage data communications between the robot controls, the sensors, and the GUI. This can be applied to the integrated sensors that are a part of any robotic device to send sensor data to the GUI for display to the user. These data can be displayed in the manner most pertinent to the therapy objectives.

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Conflicts of Interest

None

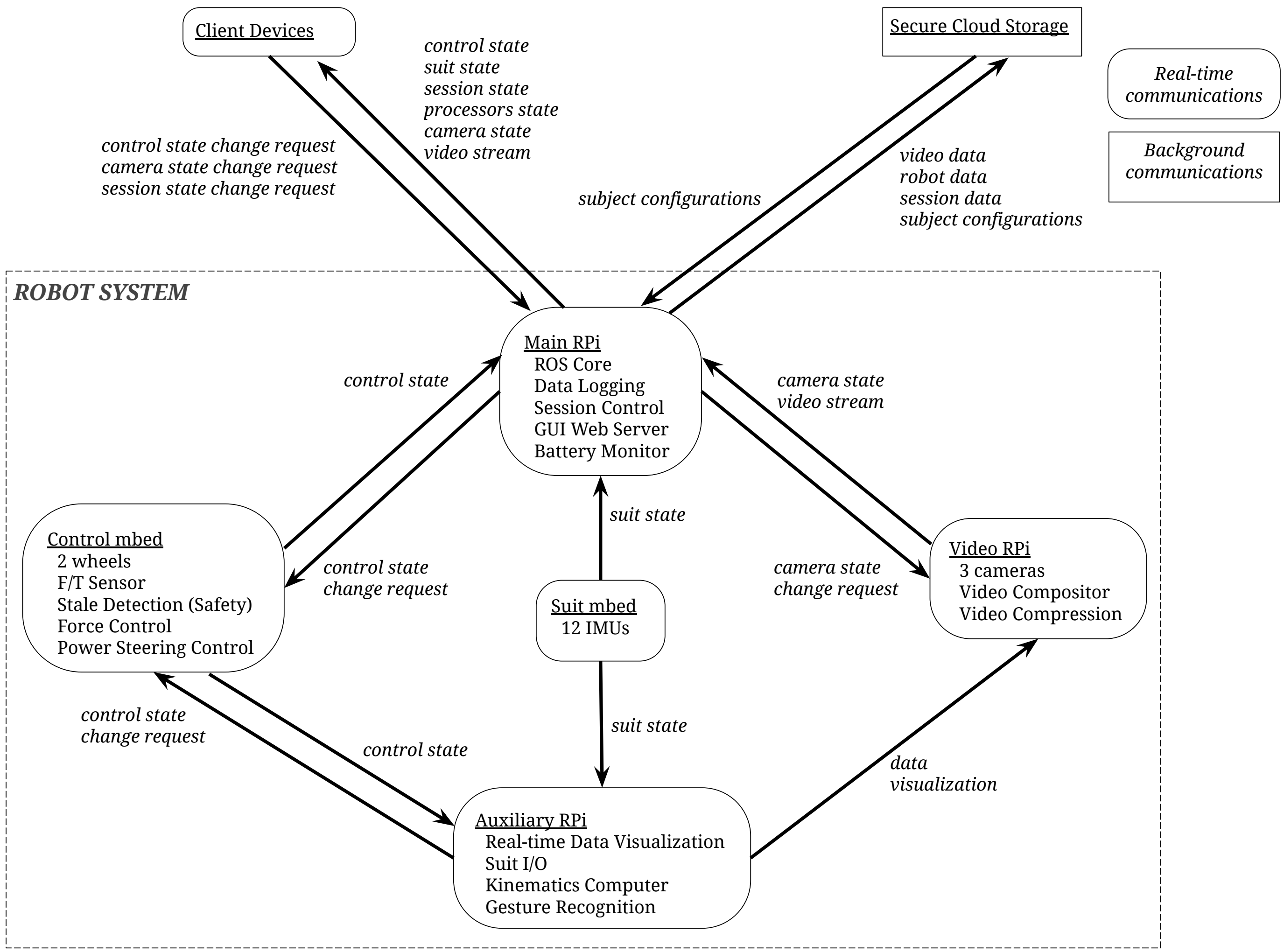

Figure 4: Data Flow Diagram. Active communications, in the rounded rectangles, refer to data transmissions during therapy sessions, such as the movement of video data between the main and video RPi's. Inactive communications, in the rectangles, involve moving data before or after sessions. Recorded session and robot data stored on the robot are uploaded to secure remote cloud storage and session configurations, parameters and notes can be downloaded, allowing different robots to be interchangeable. The control state is comprised of sensor data from the force/torque (f/t) sensor and information about the wheels' state. The control state also provides the connection status of the f/t sensor and the wheels. Control state change requests are petitions to alter the state of the wheels. The suit state consists of sensor data from the IMUs in the motion capture suit, in addition to the connection status of each sensor. The camera state contains the parameters brightness, contrast, exposure, and focus values for all three cameras. A change request for the camera petitions to adjust any of the camera parameters. The video stream is a composited video of the three camera views and a set of data plots. The session state is an amalgamation of information about the current session and trial, such as the subject number, if data recording has started, if the trial has started, the trial number, and the attending therapist. Session state requests petition to alter aspects of the session state such as requesting to start recording or selecting a subject. Processors states describe the CPU load and available memory and disk space for each of the RPi's. The recorded robot, video, and session data are uploaded to secure cloud storage after the session has ended and once the robot is connected to the internet via an Ethernet connection on the main RPi. The subject parameter sets and session notes can be uploaded and downloaded as well.

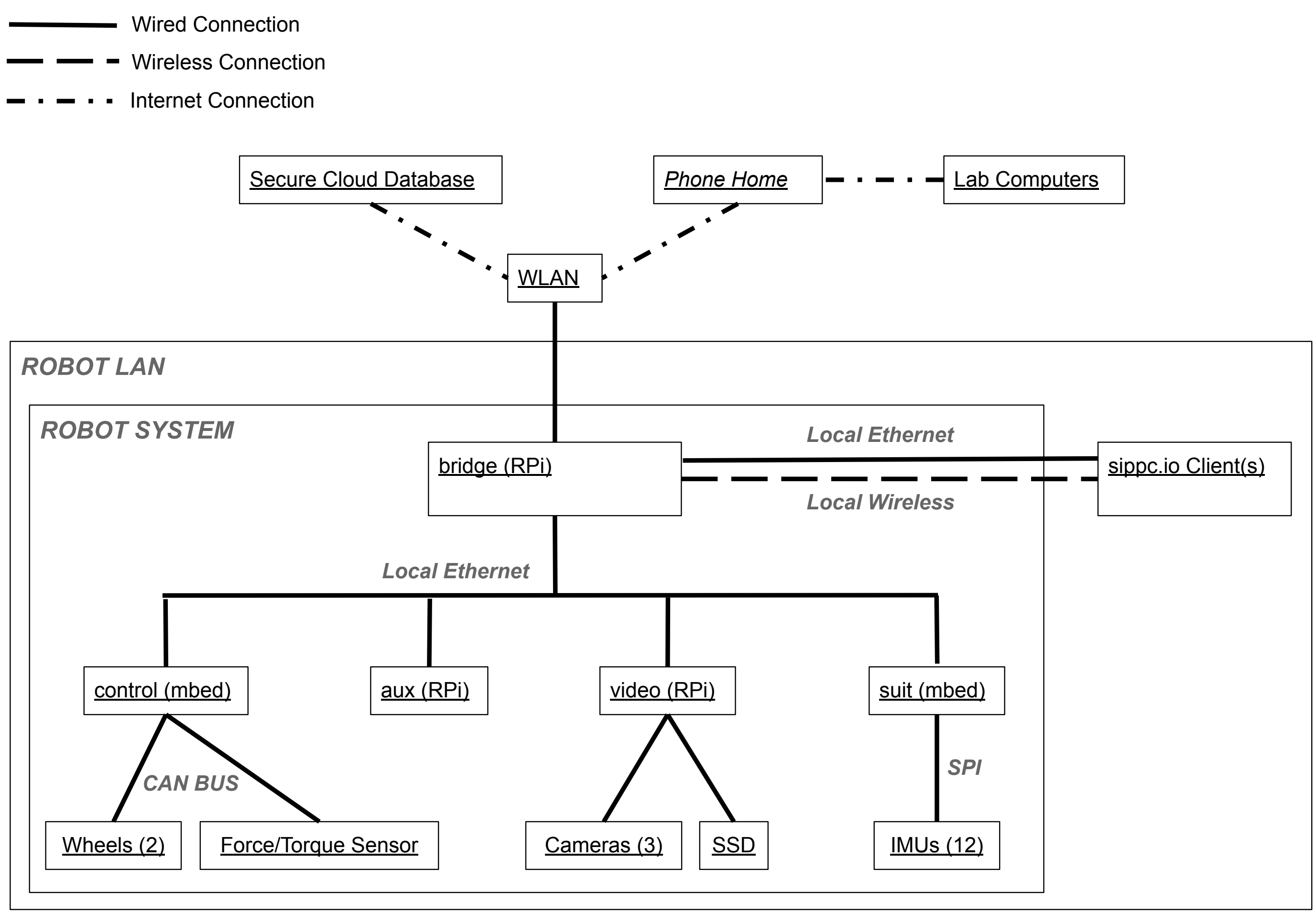

Figure 5: Diagram of network and device connections. The robot has five specialized processors (RPi's and two Mbed microprocessors) that communicate via Ethernet. The main RPi acts as an access point and web server broadcasting the SIPPC local network and GUI. The robot is connected to the internet through main RPi to synchronize data between secure remote machines and other SIPPC robots. The video RPi (sippcvideo) is dedicated to capturing and compositing the camera videos and data plots. The control Mbed (sippccontrol) monitors and manipulates the wheels and force/torque (F/T) sensor. The suit Mbed is connected to 12 IMUs on the motion capture suit.

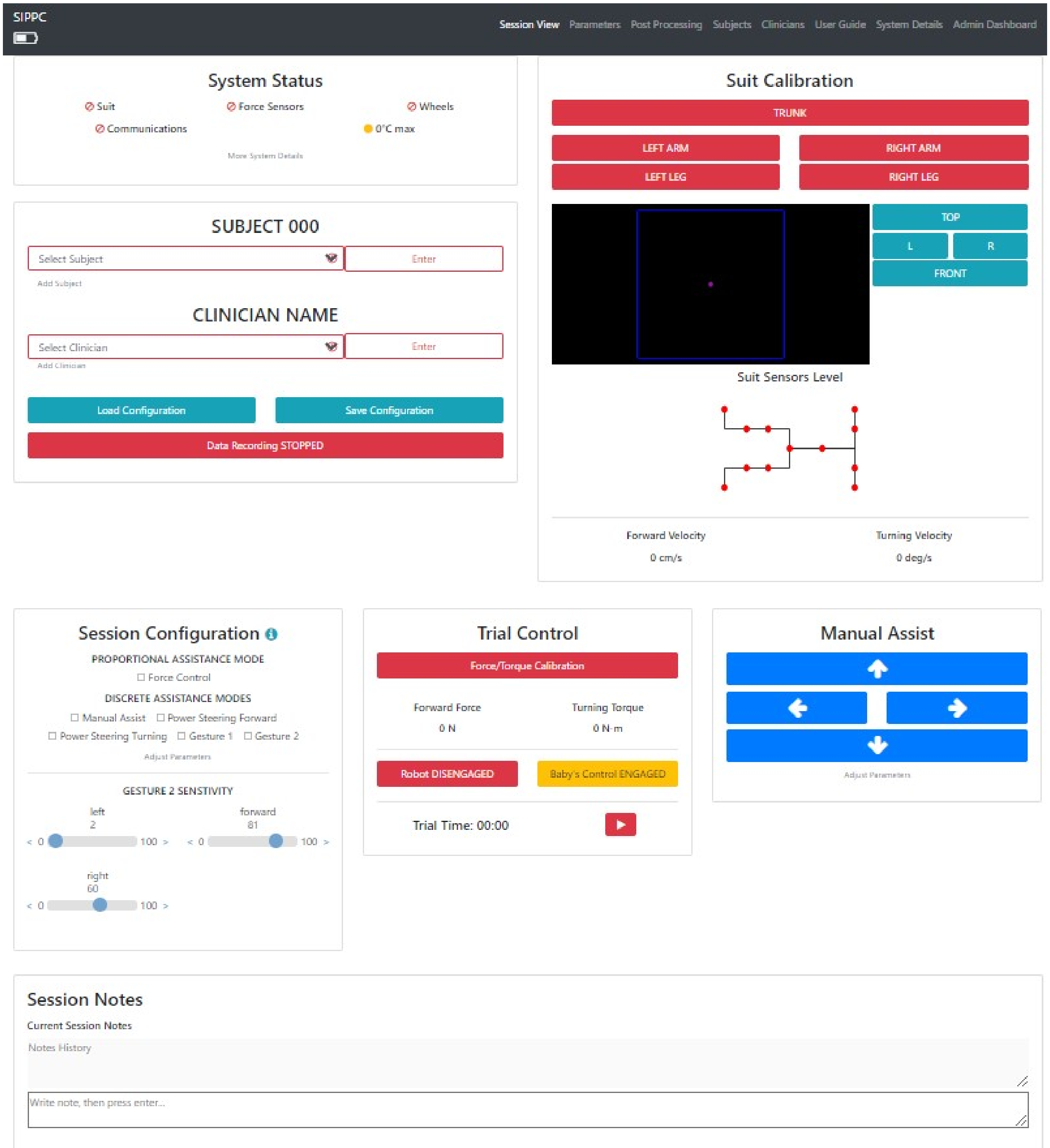

Figure 6: Session view is the main page, consisting of the most relevant operations necessary for the therapists to perform therapy sessions and provide the infant with as much attention as possible. Therapists receive a summary of the robot status (System Status), can select the infant code and therapist name, calibrate the suit, view velocity, force, and infant limb data in real-time, modify robot control modes and parameters (Session Configuration), manage the trial, drive the robot (Manual Assist), and write notes about the active session.

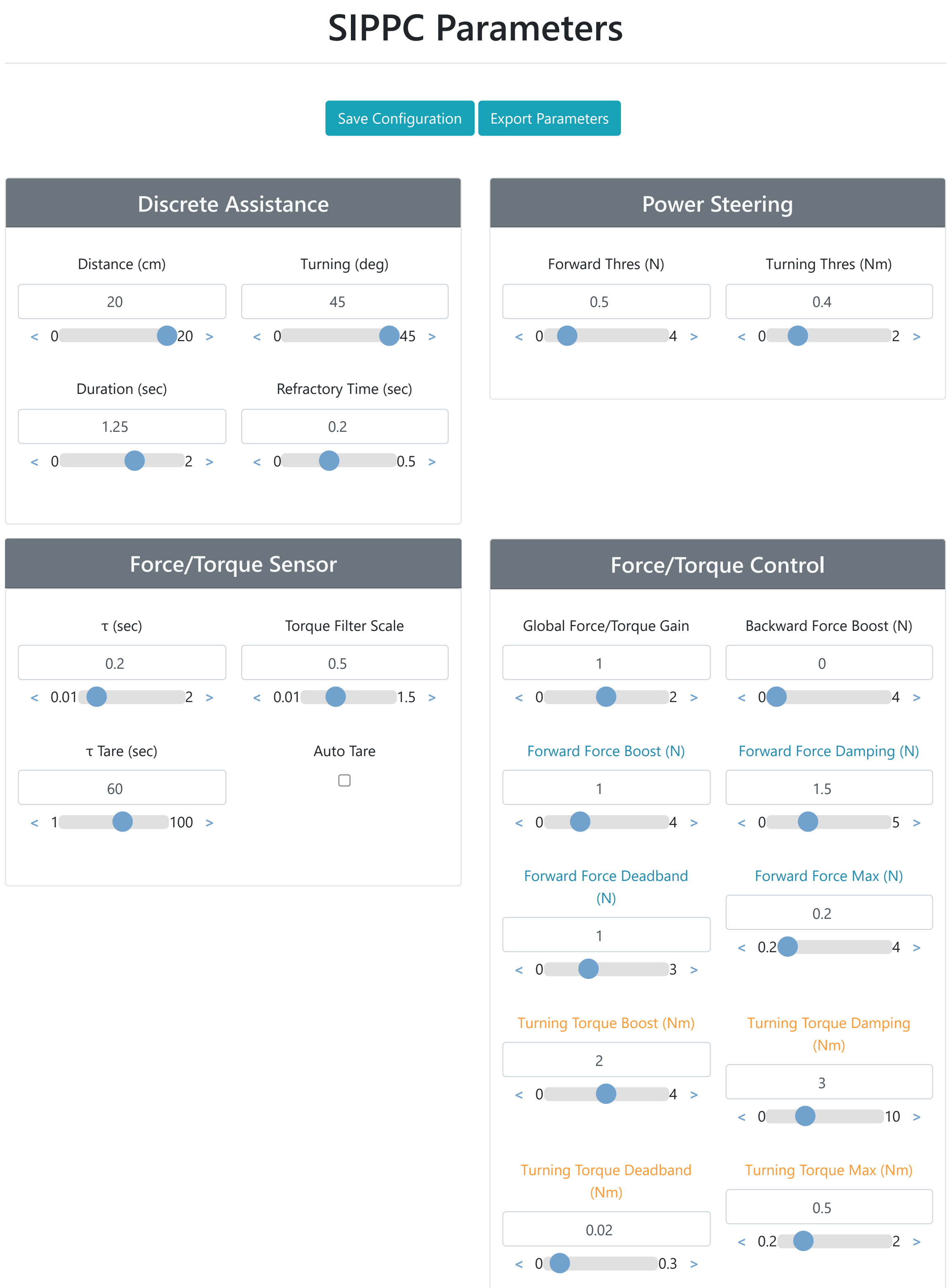

Figure 7: Parameter page for adjusting how the robot responds to infant movements. Discrete assistance parameters specify the distance, angle, duration, and time between discrete robot assistance triggers. Power steering parameters specify the threshold GRFs that trigger robot assistance. Force/Torque Sensor parameters manage the filtering of the sensor noise. Force/Torque Control parameters specify the magnitude of the proportional force assistance.

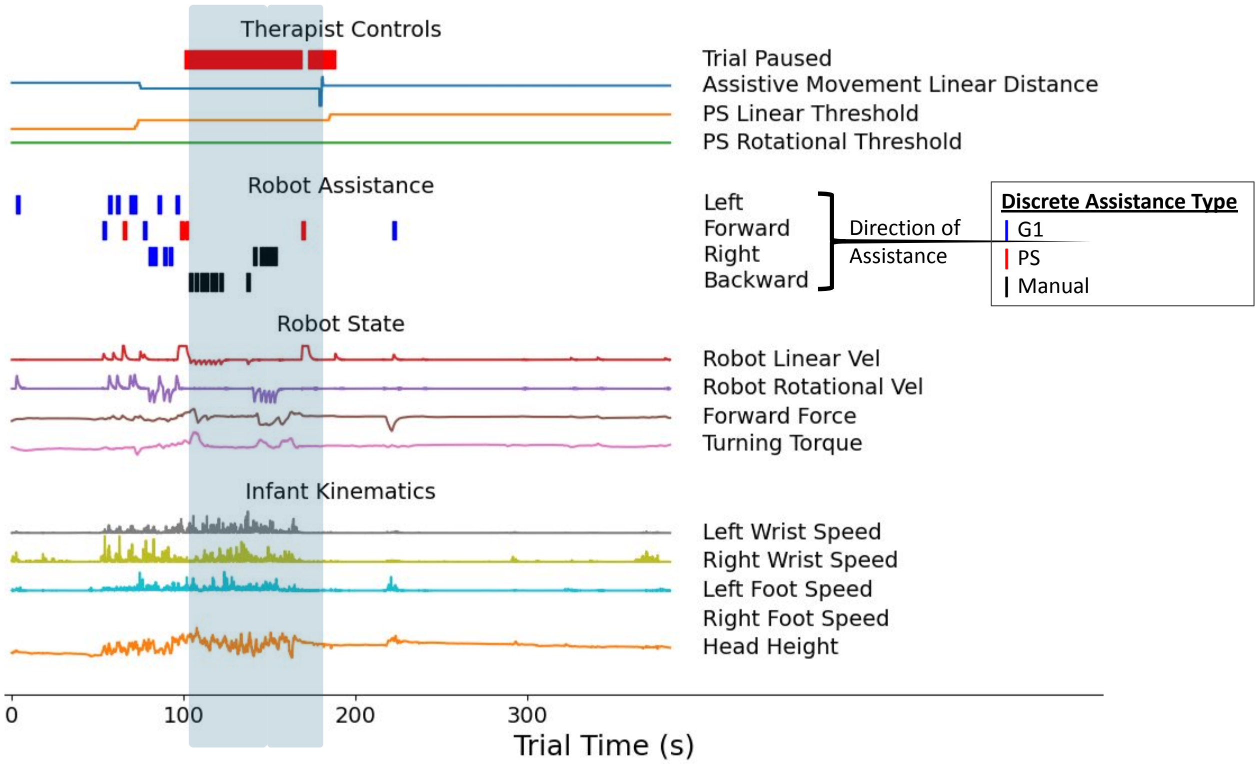

Figure 8: Summary of select robot and parameter data during one trial for infant LL011, during Week 4. The section titled Therapist Controls contains some of the parameters in the GUI that the therapist can adjust to personalize the motor training trial (PS is power steering). Therapists can pause the trial (Trial Paused), adjust the linear distance the robot moves when the infant triggers an assistive response (Assistive Movement Linear Distance in centimeters), adjust the linear GRF threshold (in Netwons) to trigger PS, and adjust the rotational GRF threshold (in Newton-meters) to trigger PS. The Robot Assistance section shows the discrete robot assistance events that are triggered by the infant's movements as vertical tick marks. Black indicates manual assistance where the therapist drives the robot, red indicates power steering, and blue indicates Gesture 1 (G1). The Robot State section shows the robot velocities (in cm/s) and sensed forward forces (in Newtons) and turning torque (in Newton-meters). The Infant Kinematics section shows the infant limb speeds (in cm/s) for the wrists and feet, as well as the height of the head (in centimeters). The light blue box highlights a region when the therapist paused the trial, right after the infant made a series of forward movements triggered by Power steering in red under Robot Assistance. While the trial is paused, the therapist manually moved the SIPPC, indicated in black under the Robot Assistance. In this particular trial, the right foot sensor was not collecting data due to wear-and-tare on the cable. However, the SIPPC and GUI still operate functionally for therapeutic purposes despite a sensor missing.

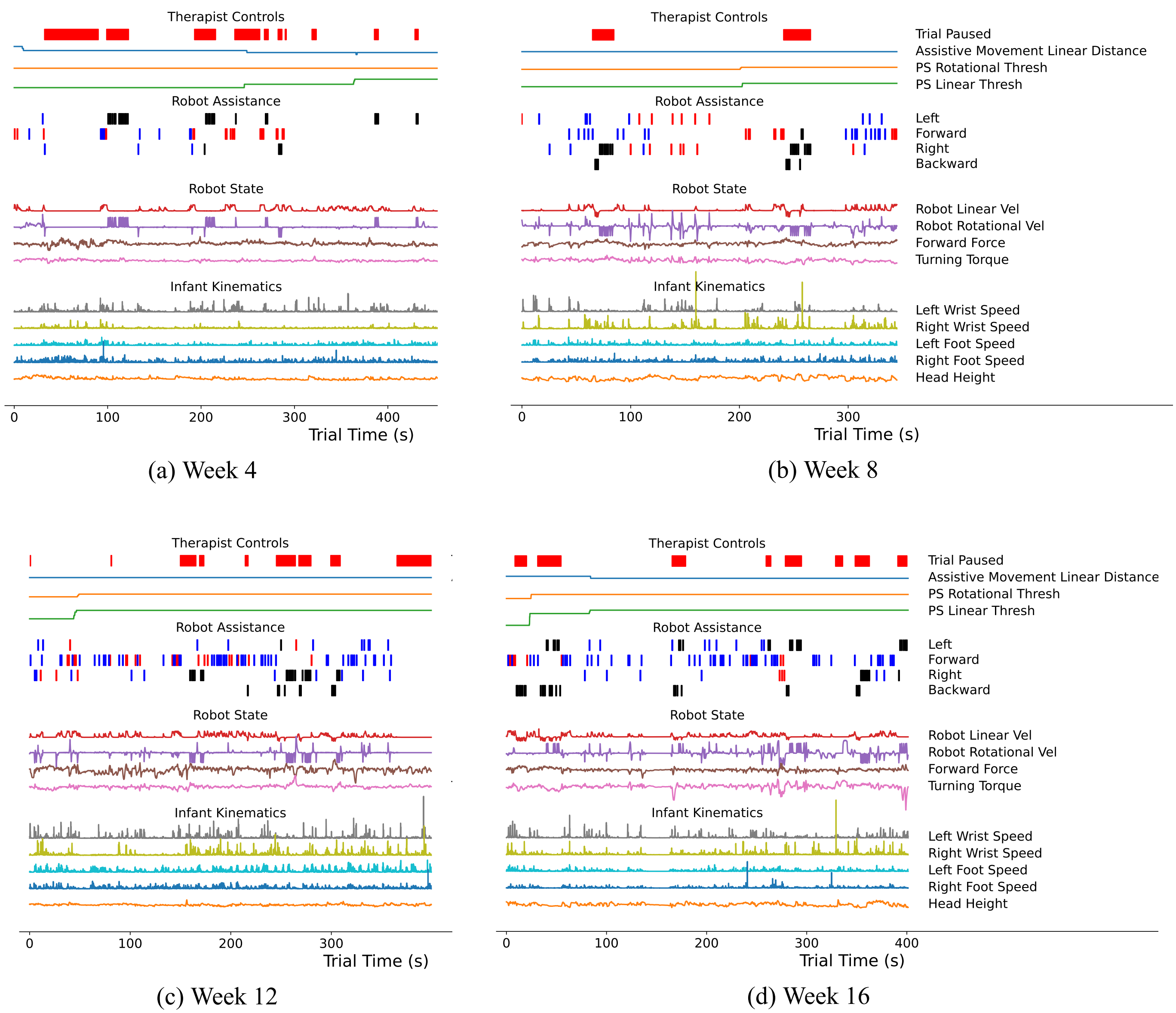

Figure 9: Longitudinal changes observed during trials for one infant

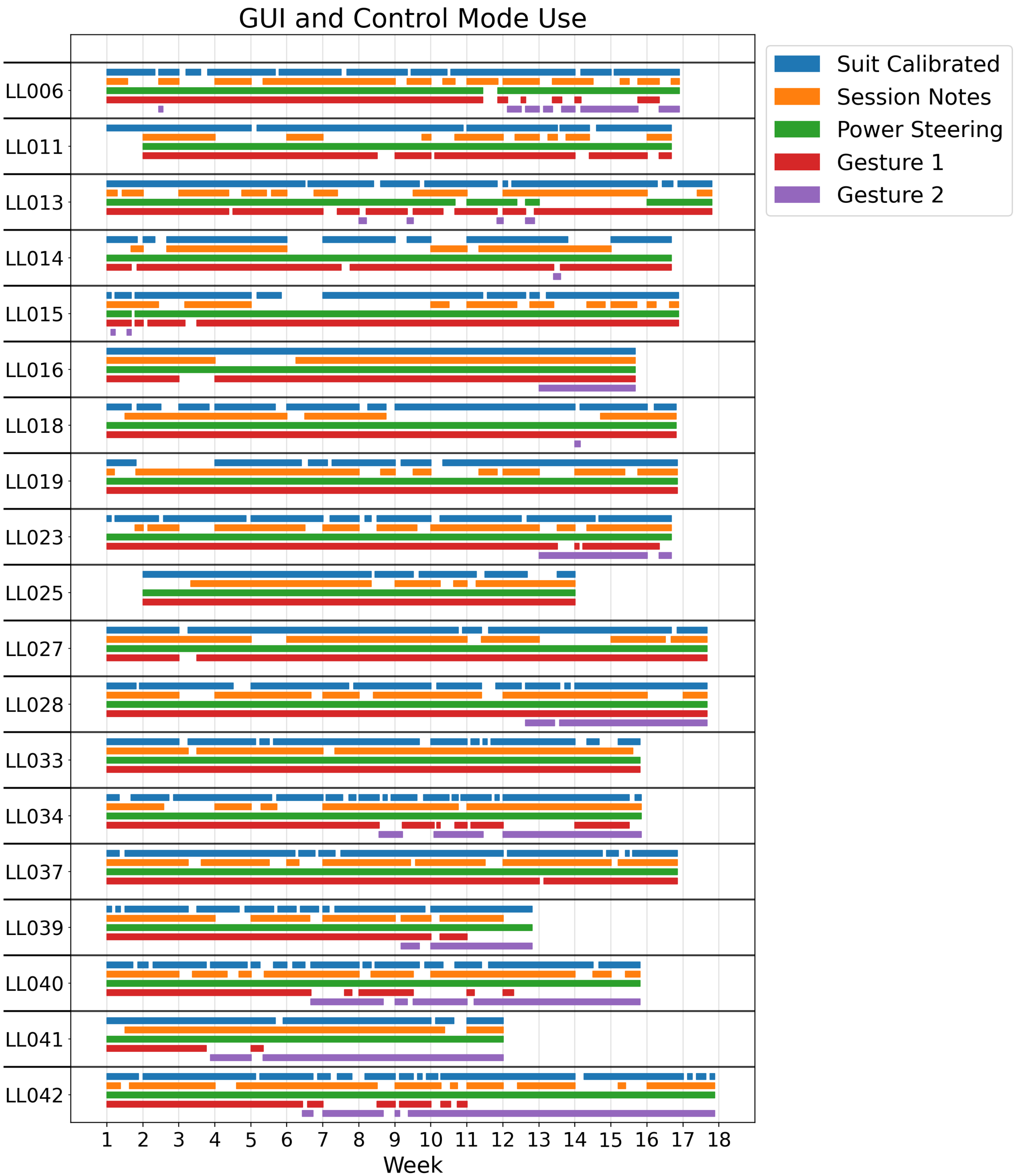

Figure 10: Use of GUI operations (suit calibration and session notes) and control modes (Power Steering, Gesture 1, and Gesture 2) across trials and infants. The bars for suit calibration indicate the suit was calibrated before starting the trial. The bars for the session notes indicate that the therapists wrote notes during the session. The bars for the control modes indicate when the therapists enabled the control mode for at least 50% of the trial duration.

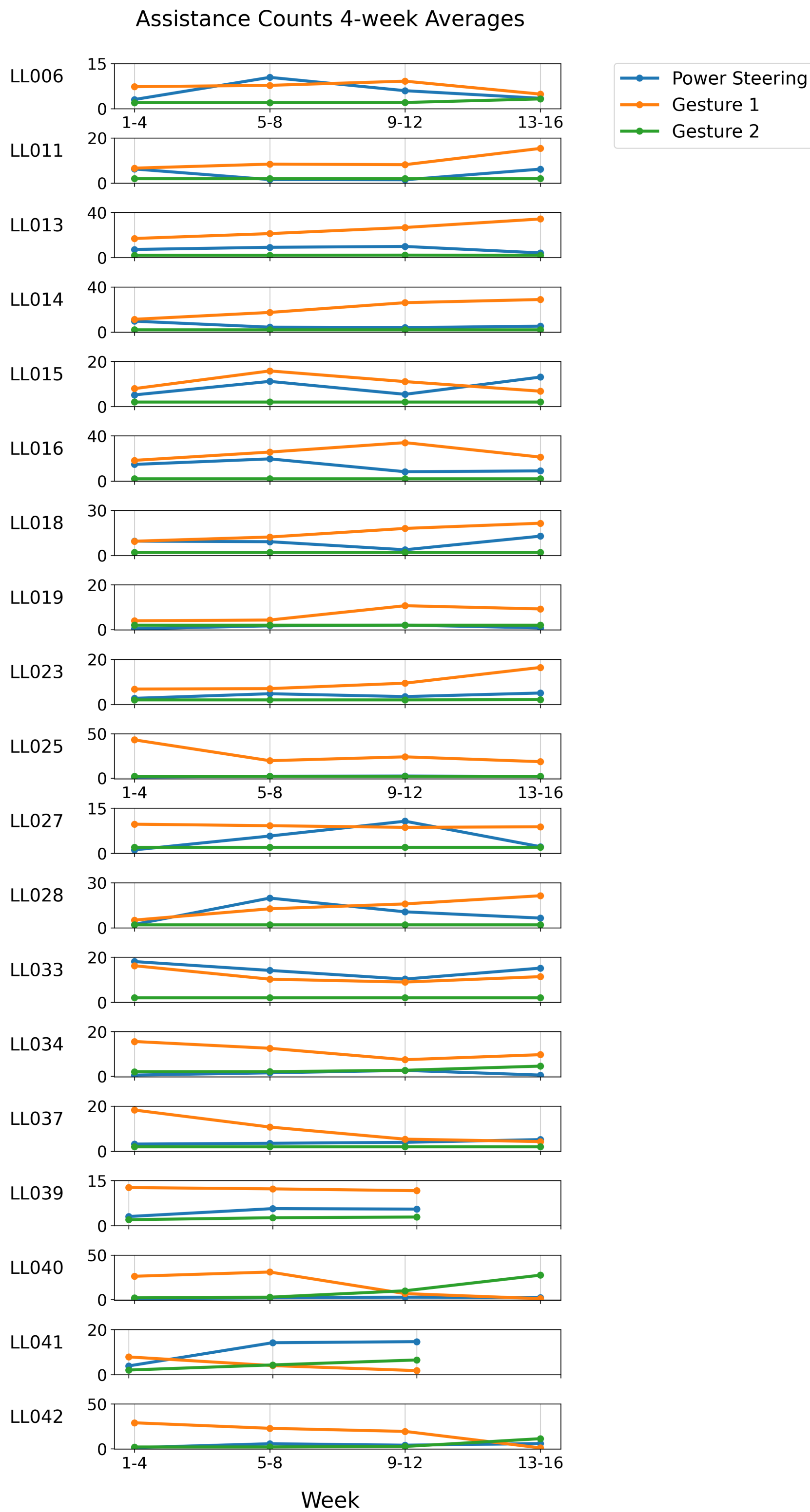

Figure 11: 4-week averages of the assistance counts for 19 infants. Assistance counts for Power steering (PS), Gesture 1 (G1), and Gesture 2 (G2) are presented here as averages of every 4 weeks. G2 is rarely turned on, thus few assistance events are triggered for it overall. G1 is more commonly the most triggered assistance type for most infants, such as LL011 and LL013. For some infants, we see a steady increase in the average assistance counts for PS or G1. For some infants, these trends appear relatively constant or decrease. These counts are influenced both by infant behavior and therapist decisions.

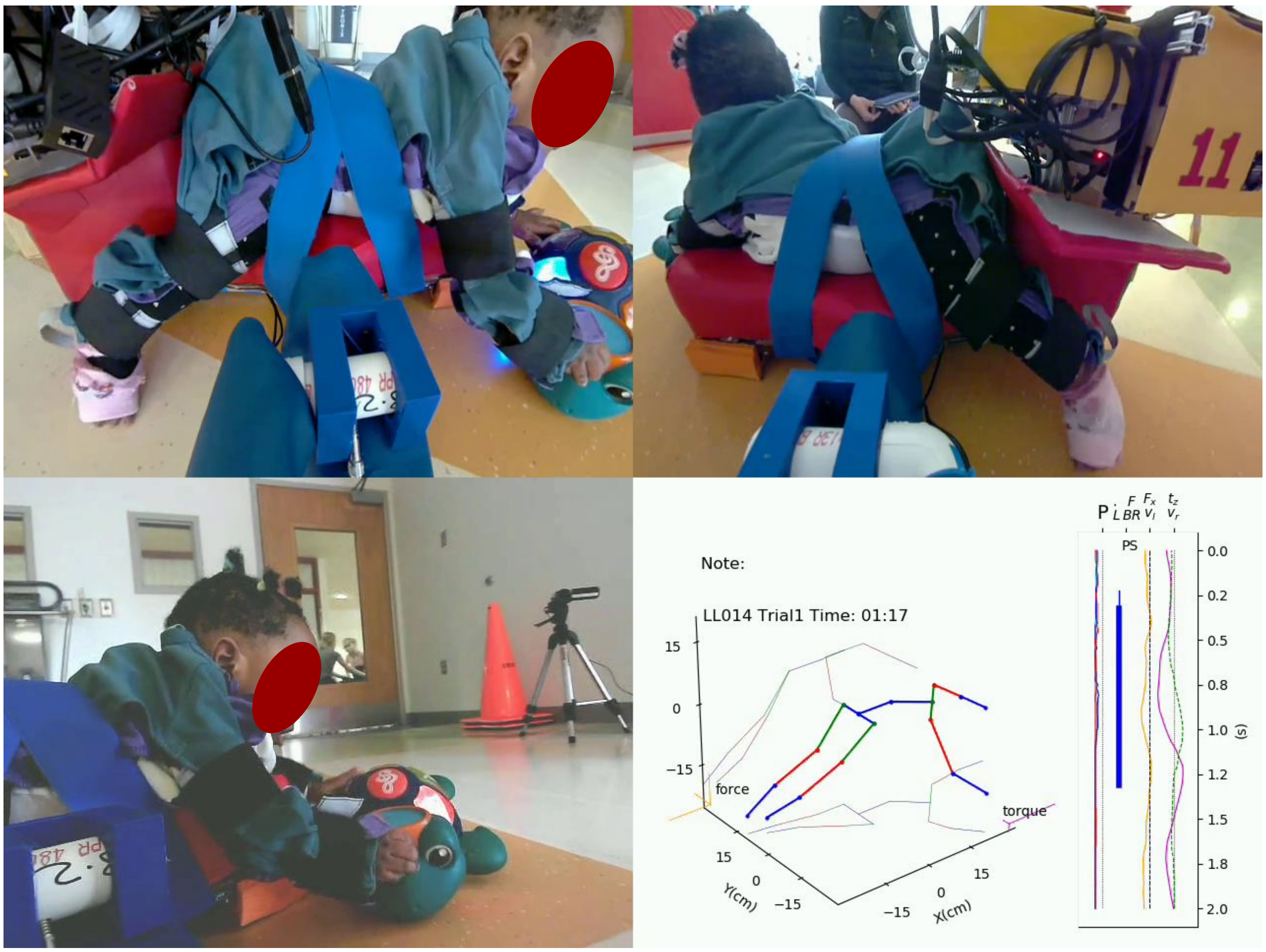

Figure 12: Real-time Video Feed. The top two panels capture all the limbs from the tip of the toes to the hands. The bottom left panel captures the front of the infant and what the infant is looking at. The bottom right quadrant shows a subset of the captured data. The kinematic skeleton of the limb and trunk positions are displayed along with the corresponding force/torque, robot velocity, and discrete assistance.

Supplemental Materials

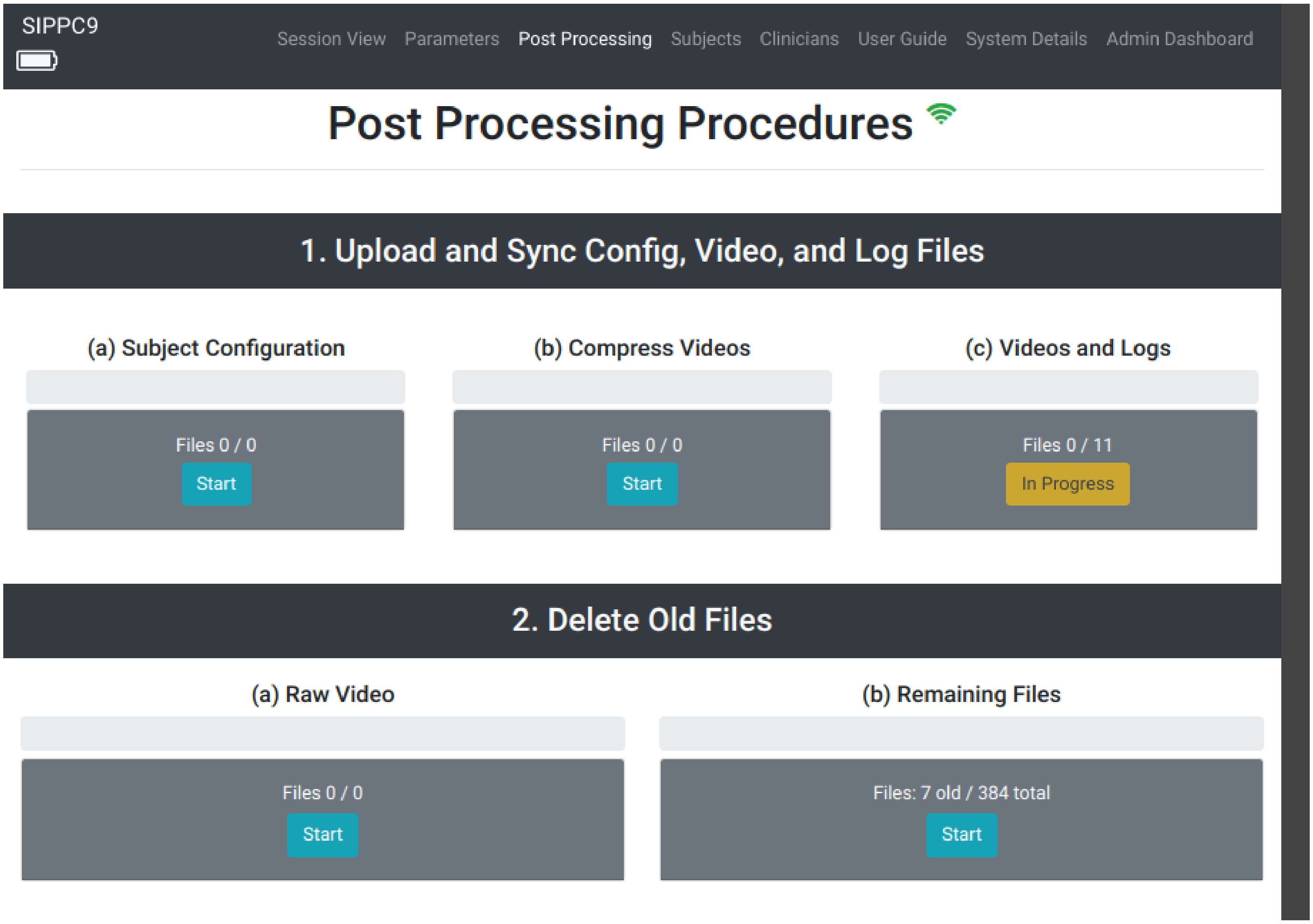

Figure S1: Post Processing page for synchronizing data with the cloud database and compressing the video files before uploading. The green WiFi symbol at the top right of the page indicates whether there is an internet connection to perform the data uploading. Data can be deleted only after it has been uploaded to free up space on the robot. The data management steps are presented in the order of their intended operation and cannot be performed while the data is recording for a session.

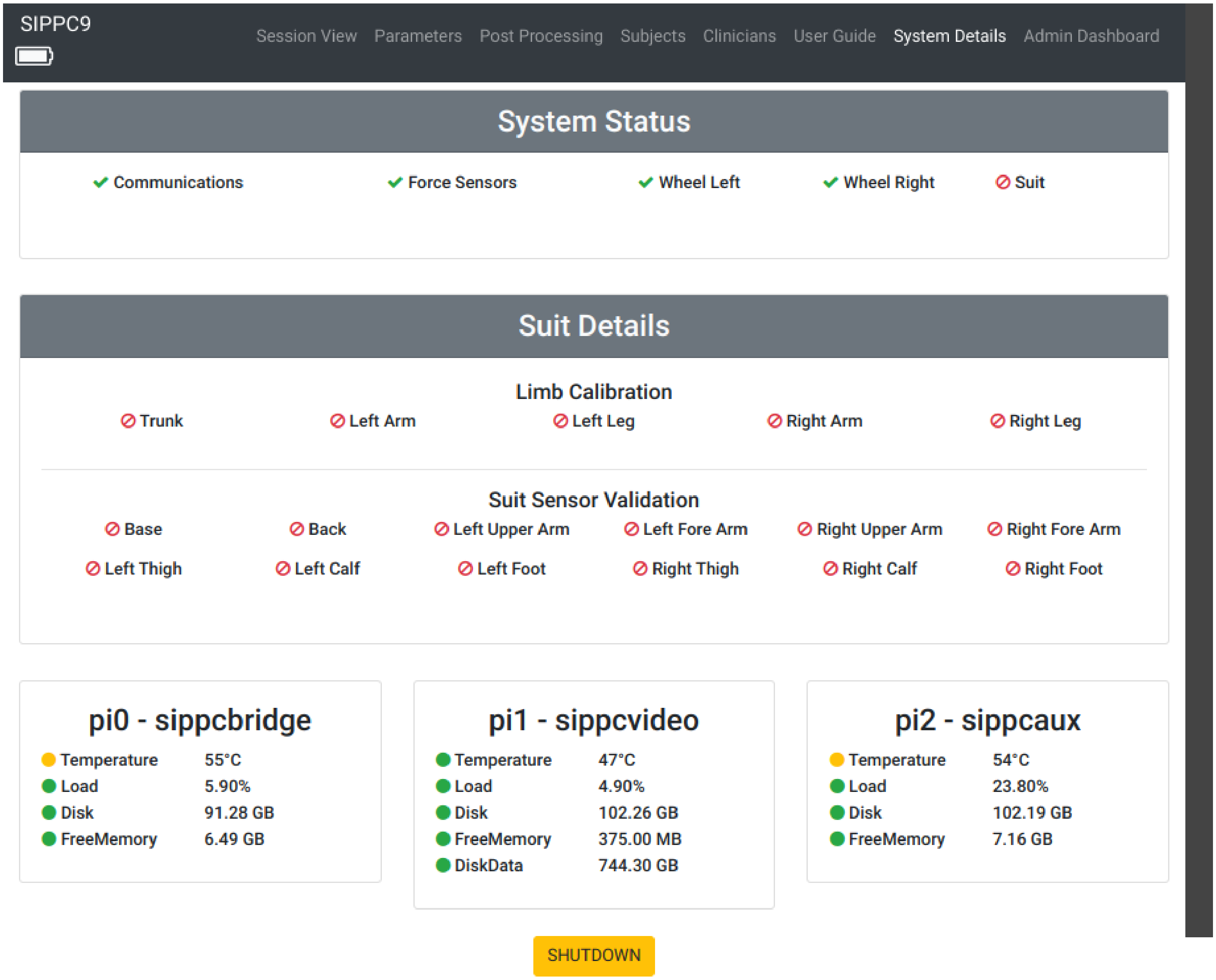

Figure S2: System Details page for diagnosing issues with various aspects of the robot system. Users can view the status of each wheel and specific sensors. Users can also view details about the three main robot processors (sippcbridge, sippcvideo, and sippcux).

References

[1] M Bax, M Goldstein, P Rosenbaum, A Leviton, N Paneth, B Dan, B Jacobsson, D Damiano, and Executive Committee for the Definition of Cerebral Palsy. Proposed Definition and Classification of Cerebral Palsy. *Developmental Medicine and Child Neurology*, 47(8):571–576, 2005. doi: https://doi.org/10.1017/s001216220500112x.

[2] Novak I., Morgan C., Adde L., Blackman J., Boyd R. N., Brunstrom-Hernandez J., Cioni G., Damiano D., Darrah J., Eliasson A. C., de Vries L. S., Einspieler C., Fahey M., Fehlings D., Ferriero D. M., Fetters L., Fiori S., Forssberg H., Gordon A. M., Greaves S., Guzzetta A., Hadders-Algra M., Harbourne R., Kakooza-Mwesige A., Karlsson P., Krumlinde-Sundholm L., Latal B., Loughran-Fowlds A., Maitre N., McIntyre S., Noritz G., Pennington L., Romeo D. M., Shepherd R., Spittle A. J., Thornton M., Valentine J., Walker K., White R., and Badawi N. Early, accurate diagnosis and early intervention in cerebral palsy: Advances in diagnosis and treatment. *JAMA Pediatrics*, 171, 2017. doi: 10.1001/jamapediatrics.2017.1689.

[3] D. R. Patel, M. Neelakantan, K. Pandher, and J. Merrick. Cerebral palsy in children: a clinical overview. *Translational pediatrics*, 9(1):S125–S135, 2020. doi: https://doi.org/10.21037/tp.2020.01.01.

[4] Diane L Damiano. Activity, Activity, Activity: Rethinking Our Physical Therapy Approach to Cerebral Palsy. *Physical Therapy*, 86(11):1534–1540, 2006. doi: https://doi.org/10.2522/ptj.20050397.

[5] Catherine Morgan, Johanna Darrah, Andrew M Gordon, Regina Harbourne, Alicia Spittle, Robert Johnson, and Linda Fetters. Effectiveness of Motor Interventions in Infants with Cerebral Palsy: A Systematic Review. *Developmental Medicine and Child Neurology*, 58(9):900–909, 2016. doi: https://doi-org.ezproxy.lib.ou.edu/10.1111/dmcn.13105.

[6] Diane L. Damiano. Rehabilitative Therapies in Cerebral Palsy: the good, the not as good, and the possible. *Journal of Child Neurology*, 24:1200–1204, 2009. doi: https://doi.org/10.1177/0883073809337919.

[7] C. Morgan, I. Novak, R. C. Dale, Andrea Guzzetta, and Nadia Badawi. Game (goals - activity - motor enrichment): protocol of a single blind randomised controlled trial of motor training, parent education and environmental enrichment for infants at high risk of cerebral palsy. *BMC Neurology*, 14(1):203, 2014. doi: https://doi.org/10.1186/s12883-014-0203-2.

[8] Karen E. Adolph. Learning to Move. *Current Directions in Psychological Science*, 17(3):213–218, 2008. doi: https://doi.org/10.1111/j.1467-8721.2008.00577.x.

[9] Max Horovitz and Johnny L. Matson. Developmental Milestones in Toddlers with Atypical Development. *Research in Developmental Disabilities*, 32(6):2278–2282, 2011. ISSN 0891-4222. doi: https://doi.org/10.1016/j.ridd.2011.07.039. URL https://www.sciencedirect.com/science/article/pii/S0891422211002964.

[10] D.I. Anderson, J.J. Campos, D.C. Witherington, A. Dahl, M. Rivera, M He, I Uchiyama, and M Barbu-Roth. The Role of Locomotion in Psychological Development. *Frontiers in Psychology*, 4:440, 2013. doi: https://doi.org/10.3389/fpsyg.2013.00440.

[11] Karen E Adolph, Beatrix Vereijken, and Mark A Denny. Learning to Crawl. *Child Development*, 69:1299–1312, 1998. doi: https://doi.org/10.1111/j.1467-8624.1998.tb06213.x.

[12] Q. L. Xiong, X. Y. Wu, Y. Liu, C. X. Zhang, and W. S. Hou. Measurement and analysis of human infant crawling for rehabilitation: A narrative review. *Frontiers in Neurology*, 12, 2021. doi: https://doi.org/10.3389/fneur.2021.731374.

[13] A. Gonzalez, L. Garcia, J. Kilby, and Peter McNair. Robotic devices for paediatric rehabilitation: a review of design features. *BioMedical Engineering OnLine*, 20(89), 2021. doi: https://doi.org/10.1186/s12938-021-00920-5.

[14] R. Kabir, M. S. H. Sunny, H. U. Ahmed, and M. H. Rahman. Hand Rehabilitation Devices: A Comprehensive Systematic Review. Micromachines. *Current physical medicine and rehabilitation reports*, 13 (7):1033, 2022. doi: https://doi.org/10.3390/mi13071033.

[15] Alan W Salmoni, Richard A Schmidt, and Charles B Walter. Knowledge of Results and Motor Learning: A Review and Critical Reappraisal. *Psychological Bulletin*, 95(3):355–386, 1984. doi: https://doi.org/10.1037/0033-2909.95.3.355.

[16] Tomoko Kitago and John W Krakauer. Motor Learning Principles for Neurorehabilitation. *Handbook of Clinical Neurology*, 110:93–103, 2013. doi: https://doi.org/10.1016/b978-0-444-52901-5.00008-3.

[17] Danielle Levac, Laurie Wishart, Cheryl Missiuna, and Virginia Wright. The Application of Motor Learning Strategies within Functionally Based Interventions for Children with Neuromotor Conditions. *Pediatric Physical Therapy*, 21(4):345–355, 2009. doi: https://doi.org/10.1097/PEP.0b013e3181beb09d.

[18] Valerie Pomeroy, Salvatore M Aglioti, Victor W Mark, Dennis McFarland, Cathy Stinear, Steven L Wolf, Maurizio Corbetta, and Susan M Fitzpatrick. Neurological Principles and Rehabilitation of Action Disorders: Rehabilitation Interventions. *Neurorehabilitation and Neural Repair*, 25(5):33S–43S, 2011. doi: https://doi.org/10.1177/1545968311410942. URL https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4139494/.

[19] Catherine P. Adans-Dester, Nicolas Hankov, Anne T. O'Brien, Gloria P. Vergara-Diaz, Randie M. Black-Schaffer, Ross D. Zafonte, Jennifer Dy, Sunghoon Ivan Lee, and Paolo Bonato. Enabling Precision Rehabilitation Interventions using Wearable Sensors and Machine Learning to Track Motor Recovery. *NPJ Digital Medicine*, 3 1:121, 2020. doi: https://doi.org/10.1038/s41746-020-00328-w.

[20] A Moinuddin, A Goel, and Y Sethi. The Role of Augmented Feedback on Motor Learning: A Systematic Review. *Cureus*, 13(11), 2021. doi: https://doi.org/10.7759/cureus.19695.

[21] Thubi H. A. Kolobe and Andrew H. Fagg. Robot Reinforcement and Error-Based Movement Learning in Infants With and Without Cerebral Palsy. *Physical Therapy*, 99(6):677–688, 2019. doi: https://doi.org/10.1093/ptj/pzz043.

[22] H.A. Kolobe, A. Fagg, Peter Pidcoe, and P. Williams. Effectiveness of Reward-and Error-Based Movement Learning in Enhancing Self-Initiated Prone Locomotion in Infants with or at Risk for Cerebral Palsy. *Physiotherapy*, 101:e781–e782, 05 2015. doi: https://doi.org/10.1016/j.physio.2015.03.3658.

[23] Mustafa A Ghazi, Michael D Nash, Andrew H Fagg, Lei Ding, Thubi H A Kolobe, and David P Miller. *Novel Assistive Device for Teaching Crawling Skills to Infants*, volume 113, pages 593–605. Springer International Publishing, 2016. doi: https://doi.org/10.1007/978-3-319-27702-8_39.

[24] Tummy Time Toys | Best Crawling Toys | Crawligator. https://www.thecrawligator.com/. Accessed: March 11, 2024.

[25] Jack Mcnamara. Redbarn Enterprises Inc. https://redbarn-enter.com/. Accessed March 11, 2024.

[26] J. Laut, M. Porfiri, and P. Raghavan. The Present and Future of Robotic Technology in Rehabilitation. *Current Physical Medicine and Rehabilitation Reports*, 4(4):312–319, 2016. doi: https://doi.org/10.1007/s40141-016-0139-0.

[27] David Miller, Andrew Fagg, Lei Ding, Thubi Kolobe, and Mustafa Ghazi. Robotic Crawling Assistance for Infants with Cerebral Palsy. 01 2015.

[28] Johanna Renny Octavia, Jorn Ockerman, Jamil Joundi, Arno Penders, and Jelle Saldien Lynn Bar-On. Matti: Tangible user interface for engaging patients in physical therapy towards a motivating rehabilitation. *International Journal of Technology*, 15(3):697–708, May 2024. ISSN 2087-2100. doi: https://doi.org/10.14716/ijtech.v15i3.6118.

[29] Luke A Tucker, Ji Chen, Lauren Hammel, Diane L Damiano, and Thomas C Bulea. An open source graphical user interface for wireless communication and operation of wearable robotic technology. *Journal of Rehabilitation and Assistive Technologies Engineering*, 7:2055668320964056, 2020. doi: 10.1177/2055668320964056. URL https://doi.org/10.1177/2055668320964056. PMID: 33403122.

[30] R. Young, K. Sage, D. Broom, Andrew Hext, Nicky Snowdon, and Christine Smith. Evaluating the usability of a co-designed power assisted exercise graphical user interface for people with stroke. *Journal of NeuroEngineering and Rehabilitation*, 20(95), 2023. doi: https://doi.org/10.1186/s12984-023-01207-7.

[31] Alexander Wilkinson, Michael Gonzales, Patrick Hoey, David Kontak, Dian Wang, Noah Torname, Amelia Sinclaire, Zhao Han, Jordan Allspaw, Robert Platt, and Holly Yanco. Design guidelines for human–robot interaction with assistive robot manipulation systems. *Paladyn*, 12(1):392–401, 2021. doi: doi:10.1515/pjbr-2021-0023. URL https://doi.org/10.1515/pjbr-2021-0023.

[32] J. B. Southerland. Activity recognition and crawling assistance using multiple inexpensive inertial measurement units. Master's thesis, School of Computer Science, University of Oklahoma, 2012.

[33] Daniel Roetenberg, Henk Luinge, and Per Slycke. sens mvn: Full 6dof human motion trackingusing miniature inertial sensors. Technical report, XSENS Technologies, April 2013.

[34] Mustafa A. Ghazi, Monique O. Shotande, Thubi H. A. Kolobe, Reza J. Torbati, Julie Skorup, Stephanie Walters, Laura A. Prosser Morgan Alcott, Beth A. Smith, and Andrew H. Fagg. Robotic rehabilitation device for promoting prone locomotion skills in infants with cerebral palsy. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, in preparation.

[35] ROS. Robot operating system (ros), 2007. URL https://www.ros.org/. Last accessed 1 July 2022.

[36] Christopher Crick, Graylin Jay, Sarah Osentoski, Benjamin Pitzer, and Odest Chadwicke Jenkins. *Rosbridge: ROS for Non-ROS Users*, volume 100, pages 493–504. Springer International Publishing, 2017. doi: https://doi.org/10.1007/978-3-319-29363-9_28.

[37] Douglas Crockford. Json, 2022. URL https://www.json.org/json-en.html. Last accessed 10 July 2022.

[38] Raspberry Pi Foundation. Raspberry pi, 2012. URL https://www.raspberrypi.org/. Last accessed 10 July 2022.

[39] Pallets Team. Flask, 2010. URL https://flask.palletsprojects.com/en/2.1.x/. Last accessed 10 July 2022.

[40] Benoit Chesneau, Konstantin Kapustin, Randall Leeds, Berker Peksağ, Jason Madden, and Brett Randall. gunicorn, 2010. URL https://gunicorn.org/. Last accessed 10 July 2022.

[41] Nginx, Inc. Nginx, 2004. URL https://nginx.org/en/. Last accessed 10 July 2022.

[42] Matthew Bodenhamer. *Learning Relational Concepts with the Spatiotemporal Multidimensional Relational Framework*. PhD thesis, University of Oklahoma, 2014.

[43] Thomas J. Palmer. *Learning Action-State Representation Forests for Implicitly Relational Worlds*. PhD thesis, University of Oklahoma, 2015.

[44] Peter Pidcoe and Hlapang Kolobe. Self-initiated prone progressive crawler, 01 2015.

[45] Laura A. Prosser, Julie Skorup, Samuel R. Pierce, Abbas F. Jawad, Andrew H. Fagg, Thubi H. A. Kolobe, and Beth A. Smith. Locomotor Learning in Infants at High Risk for Cerebral Palsy: A Study Protocol. *Frontiers in Pediatrics*, 11, 2023. ISSN 2296-2360. doi: https://doi.org/10.3389/fped.2023.891633. URL https://www.frontiersin.org/articles/10.3389/fped.2023.891633.

[46] M Bosanquet, L Copeland, R Ware, and R Boyd. A Systematic Review of Tests to Predict Cerebral Palsy in Young Children. *Developmental Medicine and Child Neurology*, 55(5):418–426, 2013. URL https://doi.org/10.1111/dmcn.12140.

[47] S. K. Campbell. *The Test of Infant Motor Performance. Test User's Manual Version 3.0 for the TIMP Version 5*. Infant Motor Performance Scales, LLC, Chicago, IL, 2012.