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RESEARCH ARTICLE

A User-Friendly Wearable Telerehabilitation System Based on Neuromotor Training for Mild Post-Stroke Patients: The DoMoMEA System

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ABSTRACT Home-based telerehabilitation technologies can support the long-term rehabilitation needs of post-stroke patients. This work describes an Android-based wearable system for telerehabilitation (DoMoMEA), which engages such patients in a full-body customized neuromotor rehabilitation protocol. DoMoMEA features seven inertial units and five force sensors, which capture patient's body posture, movements, and interactions with a non-immersive virtual reality environment, providing real time scores, motivational feedback, and online automatic corrections for performance errors. Clinically relevant parameters can be collected and sent to a remote server where they can be retrieved by a physiotherapist through a dedicated web application, according to a store-and-forward telemedicine approach. Clinicians can also personalize the training settings to ensure a high level of engagement and challenge for patients, based on their residual motor abilities, needs and progress. Preliminary tests performed on 11 healthy elderly volunteers revealed a high usability of the system (82 ± 6 points in the System Usability Scale questionnaire). Furthermore, the system was presented to experienced physiatrists and physiotherapists, who provided their assessment by a semi-structured interview. The evidence underscored the usefulness of DoMoMEA not only at home, but also in daily clinical practice.

INDEX TERMS Neuromotor recovery, stroke, telerehabilitation, telemedicine, wearable system.

I. INTRODUCTION

Stroke is a leading cause of disability among the adult population, with an incidence of about 5 million patients with permanent disabilities over 15 million cases every year worldwide [1], [2]. Due to the long-term injury, stroke survivors and their families face great challenges after hospital discharge. Indeed, rehabilitative care at home is usually fragmented, poorly supervised, and often limited in time, even in most high-income countries [3]. Under these circumstances, patients cannot fully exploit neuroplasticity mechanisms typical of the adult brain, thus losing the opportunity to recover the impaired neuromotor functions or, even worse, developing ineffective, compensatory movement strategies [4], [5]. Such strategies usually determine pain on specific movements, balance deficits and muscle fatigue, thus increasing

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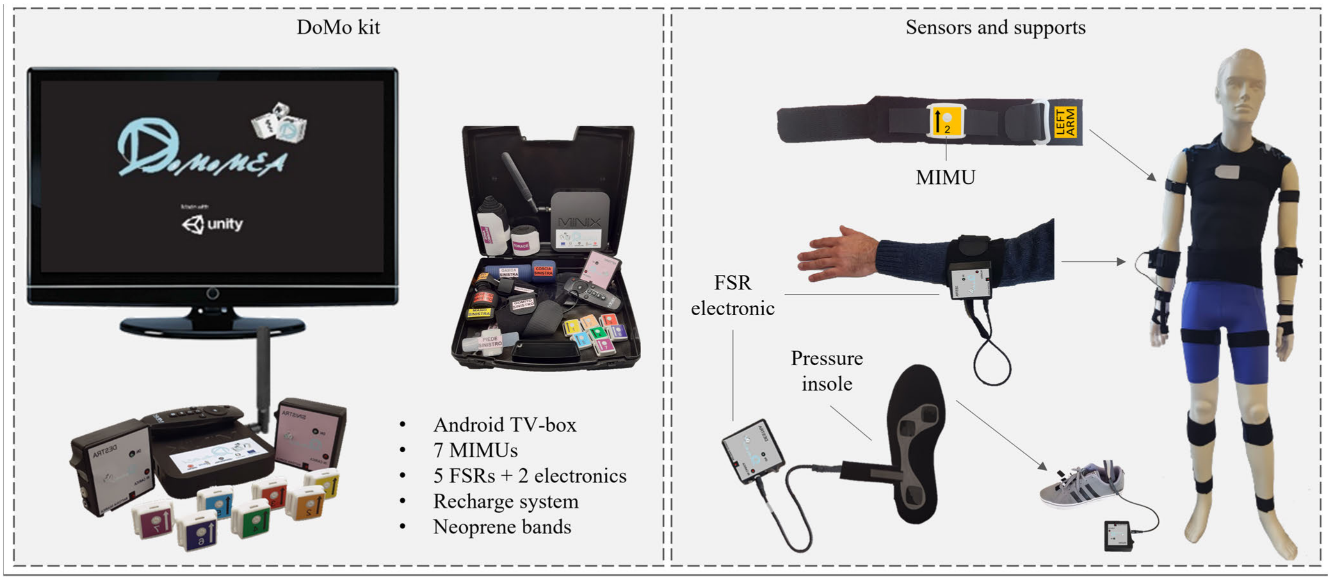

FIGURE 1. The DoMo kit of the DoMoMEA system includes an Android TV-box, seven MIMUs, five FSR sensors with two custom readout electronics, a recharge system, and a series of neoprene bands to fix the sensors on the body.

difficulty and reluctance to correct the developed strategies, with a consequent demotivation, depression and worsening of the neuropsychological as well as physical state of health [6]. On the other hand, home rehabilitation allows patients to practice surrounded by family and friends, so they receive more motivational stimuli and show greater engagement during the rehabilitation sessions [8]. Moreover, informal caregivers also provide support while the patient is approaching the systems (i.e., in semi-autonomous training) [7].

To improve compliance in exercise execution, some rehabilitation systems provide real-time feedback on patients' performance to improve their outcome (e.g., [9], [10]). Moreover, for home-based rehabilitation, it is crucial to quantify the patient's movements and progress in a reliable and reproducible way [11]. For this purpose, many technologies have been integrated in the monitoring systems so far [11], [12], such as optic sensors – e.g., the leap motion controller, the Microsoft Kinect, RGB cameras and similar (e.g., [13], [14], [15], [16], [17]) –, magneto-inertial sensors, eventually embedded in smart clothes (e.g., [18], [19], [20]), pressure sensors, possibly embedded in smart insoles or force platforms (e.g., [9], [19]), etc. In addition, innovative protocols are provided with virtual environments, with different levels of immersivity (e.g., [14], [15], [21], [22]) and adaptive control (e.g., [14], [17], [23]), to improve patients' engagement and the immersive perception during the training, also adapting its complexity and challenge to their neuropsychological and cognitive capacities, residual motor abilities, and progress [24]. Moreover, almost all rehabilitation devices are dedicated to the recovery of a specific motor skill involving different body segments (upper limbs, lower limbs, trunk, etc.) [17], [25], [26], [27], and only a few systems provide full body training, which is potentially more comprehensive and versatile [14], [28]. Despite various approaches and systems have been proposed to provide post-stroke patients with post-discharge treatment at home, none of them can solve all the existing needs and open challenges.

In this paper, we propose the DoMoMEA system, a novel low-cost portable Android-based telerehabilitation apparatus, preliminarily presented in [19] and further developed and studied, which implements semi-autonomous unsupervised full-body rehabilitation protocol for mildly impaired post-stroke patients exploiting magneto-inertial measurement units (MIMUs) and force-sensing resistors (FSRs), combined with a non-immersive virtual reality environment, which provides intuitive feedback to the patient in real-time. The system was developed with experts in the field of neurorehabilitation, and taking into account the different stakeholder's needs (patients, caregivers, and therapists).

The system implements a store-and-forward telemedicine framework, which sends remotely a synthesis of clinically relevant parameters, by enabling constant monitoring by physiotherapists. In addition, the clinician can interact with the patient by a messaging service and personalize the parameters of the protocol based on the motor abilities and progress exhibited by the patient. Common security approaches enable the safe management of patients' personal data.

II. THE DOMOMEA SYSTEM

DoMoMEA provides a wearable, portable, low-cost, store-and-forward telemedicine system expressly designed for the neuromotor long-term tele-rehabilitation of post-stroke outpatients. It is composed of two main parts, which are detailed in the following paragraphs:

A) the system used by the patient at home (called DoMo),

B) the telemedicine framework, consisting of the server and the web application.

A. SYSTEM HARDWARE

1) HARDWARE COMPONENTS

The DoMo (Fig. 1) is the core of the DoMoMEA system, and it is used by the patient at home. It is composed of (i) a low-cost Android-based host device with Bluetooth connectivity; (ii) a screen with built-in speakers (e.g., patient's TV) providing the audio-visual feedback during the exercise; iii) a set of wireless wearable nodes and the associated neoprene (styrene butadiene rubber) straps for fixing them on the body.

Although, any Android host device with Bluetooth Classic assets could be used (BT 3.0, which limits to seven the number of contemporarily connected sensors), adequate computational capabilities of medium-to-high-end devices are required for smooth operations. For this reason, we selected the MINIX-NEO U9-H Android TV-box, which features an Android Marshmallow 6.0.1 OS, 2 GB DDR3 (32-bit) RAM, a Mali-820 MP3 GPU, and an octa-core Cortex A53 Processor (64-bit). This low-cost TV-box can render videos at 60 fps. Seven magneto-inertial measurement units (MIMUs) (Multisensor Inertial SysTem - MIST, by 221e srl, Italy) are included in each DoMo kit. Each MIMU embeds a tri-axial gyroscope (±2000 deg/s), accelerometer (±16 g), and magnetometer, a 32-bit ARM Cortex-M4 microprocessor, a dual-mode BT v3.0 module, and local storage (up to 256 kB single bank Flash, 64 kB of SRAM including 16 kB with hardware parity check, Quad SPI memory interface), and it is powered by a 155 mAh rechargeable lithium battery. The size (33 × 28 x 16 mm) and weight (12 g) of MIMUs are negligible compared to those of the body segments they are applied to, which is important to avoid limiting the subject's movements and, at the same time, sensors' mutual hit. Data acquired by MIMUs (sampled at 416 Hz for both the accelerometer and gyroscope, and at 100 Hz for the magnetometer) are streamed at 50 Hz during the rehabilitation sessions. The average noise level of the accelerometer and the gyroscope computed over 126 sensors amount to 1.65 mg and 0.06 deg/s, respectively.

In addition, commercial FSR sensors expressly designed for the DoMoMEA system (YETI Pressure Sensor Membrane, by 221e srl, Italy) were used to acquire the contact pressure in the insole of patient's shoe during lower limb exercises, under the elbows during balance and core stability training, and between thumb and index during pinch grip tasks (Fig. 1, right). Their shapes were customized in accordance with the anatomical site of application and the intended task. They consist of piezoresistive sensing elements enclosed in a flexible polyester substrate, featuring a linear conductance response as a function of the applied force, with linearity of ±10% and a repeatability of ±3%. In order to preserve the FSRs structure, they were embedded into textile supports (by Ortopedia Chessa srl, Italy): FSR sensors dedicated to detect elbow and pinch pressures were embodied in custom neoprene bands, whereas the sensors for plantar pressure monitoring were fully integrated into 2-mm double-layer insoles, consisting of a hypoallergenic and breathable microfiber substrate superimposed on a polymeric fabric (see Fig 1, right). A battery-powered microcontroller-based electronic acquisition and transmission unit was developed to interface FSR sensors with the Android host. Data acquisition is performed by an analog front-end, including a non-inverting operational amplifier (OPA4130, Burr-Brown) and an anti-alias filtering stage, matched with the internal ADC of the 16-bit low-power MSP430F5529 microcontroller (Texas Instruments Inc., USA). A RN4678 dual-mode module (Microchip Technology Inc.) provides all pressure information via Bluetooth Classic to the Android host [28].

For easy wearing of all the MIMUs and FSRs readout electronics, a set of custom-designed bands (by Ortopedia Chessa srl, Italy) were used. The bands were made of an open-cell 2.5-mm neoprene substrate overlaid, on one side, with a tick Velcro-plush layer, to keep the sensors in a stable and specific position during exercise. Given the selected materials, these bands are soft and flexible enough to adapt to the patient's body shape, and they can be worn directly on the skin.

2) REHABILITATION PROTOCOL

The DoMoMEA system implements a physical home-rehabilitation protocol, specifically designed for post-stroke patients with mild impairment. The protocol lasts for eight weeks and consists of fourteen exercises grouped into five blocks (see Fig. 2), each one promoting the recovery of specific neuromotor functions. According to the training block to be performed, it is necessary to use either all or a subset of the seven MIMUs, with different placement (Fig. 3), as discussed in Section II-B2.

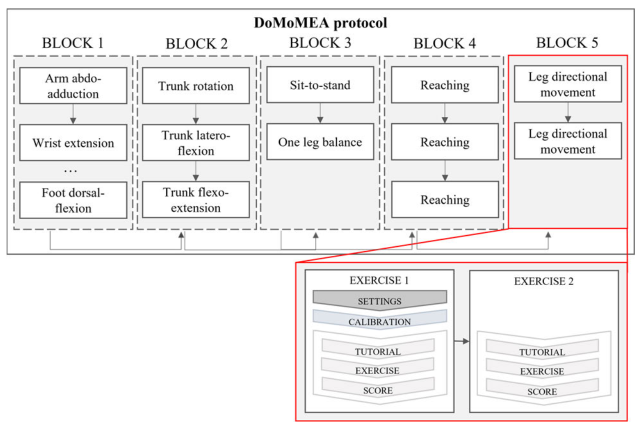

FIGURE 2. The DoMoMEA protocol and the rehabilitation session management layer protocol.

If we identify with the first letter the joint involved in the exercise, and use the subsequent letters for the movement performed, the implemented exercises can be summarized by the following acronyms (in their order of execution): SAA: shoulder abdo-adduction (AA); WFE: wrist flexion-extension (FE); EFE: elbow FE; TRV: trunk rotation around vertical axis (V); TAP: trunk rotation around antero-posterior axis (AP); TFE: trunk FE; KFE: knee FE; HFE: hip FE;

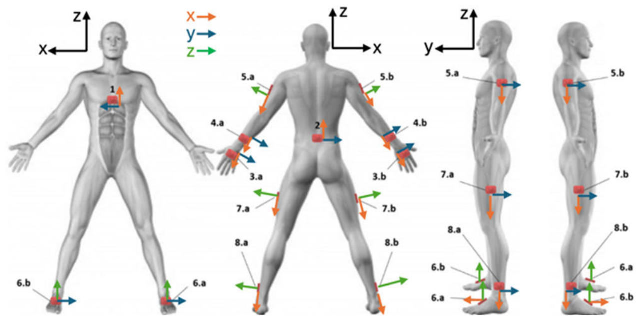

FIGURE 3. MIMUs' positioning sites. Trunk (# 2 MIMUs): (1) Chest, on the sternum, compatible with the anatomical conformation of the subject, (2) Pelvis, posteriorly, at the lumbar level (L4, L5) aligned with the spinal column. Upper limbs (# 6 sensors: 3 in the right side, and 3 in the left side): (3.a – 3.b) Hand, on the back, at the metacarpal level, (4.a – 4.b) Forearm, just above the radio-ulnar joint, (5.a – 5.b) Arm, just above the radio-ulnar joint. Lower limbs: (# 6 sensors: 3 in the right side, and 3 in the left side): (6.a – 6.b) Foot, on the back, between the tarsus and metatarsus, (7.a – 7.b) Shank, on the peroneus brevis muscle, just above the malleolus, (8.a – 8.b) Thigh, approximately halfway along the length of the vastus lateralis.

AFE: ankle FE. Each segment of interest is equipped with one MIMU. In order to facilitate this step, each unit was labeled with a colored plastic sticker reporting a printed identification number and an arrow to facilitate correct orientation, with a hole clearly indicating the position of the on–off button (see Fig. 1). The colors are used to ease the positioning on the correct body segment (Fig. 3), exploiting a visual guide in the software application. More operational details can be found in Section II-B3. Table 1 summarizes the anatomical coordinate system (ACS) for each segment and the corresponding identification method.

B. SOFTWARE ARCHITECTURE

The DoMo software architecture (Fig. 4) is composed of four layers:

1. sensors management;
2. movement tracking;
3. rehabilitation session management;
4. remote-data communication.

1) SENSORS MANAGEMENT LAYER

In the DoMoMEA system, BT communication topology is a piconet master-slave type, where the master is the Android host, whereas both MIMUs and FSRs are slaves. The user must turn on the sensing nodes at the beginning of the rehabilitation session; then, the connection is automatically established. At this point, the sensors management layer, implemented in C#, enables the full control of all sensors directly from the Unity environment (by using the BT library developed by Tech Tweaking, https://techtweaking.github.io/).

The sensor management layer operates independently of the rehabilitation exercise; MIMUs and FSRs have distinct manager and sensor-specific scripts. The manager script provides services for BT connection and disconnection, start and stop of data streaming, and orchestrates the provisioning of the data flow to the game layer. It provides sensor-related information, such as the battery level, which is used at higher levels (i.e., exercise management scripts).

Each sensor is also associated with an independent sensor script, which contains the necessary information for a single device to properly work (e.g., sampling frequency and streaming mode) and manages all its functionalities (e.g., data streaming and quality control) at a lower level.

2) MOVEMENT TRACKING LAYER

The kinematic model consisted of fourteen segments (seven for the upper body and seven for the lower body) and twelve joints (six for the upper body and six for the lower body). Each body segment was equipped with a MIMU, and the subject-specific kinematic model was calibrated to the specific subject in two steps, as specified in Table 1. The first one involved manually aligning the MIMU sensitive axes as much as possible with the ACS of the underlying body segment (see [29], section 4.2.1 - method a). The second one exploited the direction of gravity measured by the accelerometers in static conditions to define the longitudinal axis of bony segments while the subject maintained an upright posture for ten seconds (see [29], section 4.2.1 - method b). Despite the limitations of manual alignment, this procedure was chosen to enable participants to independently wear the devices at home. Each joint was modeled as a spherical joint, i.e. three degrees of freedom, with the joint coordinate system (JCS) described following the Euler angles decomposition approach (see [29], section 4.2.3) [30], [31]. As recommended by the International Society of Biomechanics (ISB) guidelines, the relevant ACSs and JCSs are graphically represented in Fig. 3 and described in Table 2.

The global reference system (GCS) of the model is defined to have the vertical axis aligned along the gravity direction, and the two horizontal axes coinciding with the thorax antero-posterior and medio-lateral axes projection onto the horizontal plane at the beginning of the recording. The following procedure for MIMU-based JCS description is general and applies to each considered joint, with the specific joints analyzed varying depending on the exercise and the block.

The angular joint kinematics estimation followed a single-body method, where the orientation of each MIMU was computed independently starting from the inertial signals integrated on board using the algorithm from Hatem et al. [32] (MAD). The MAD was selected for its computation efficiency compared to other state-of-the-art complementary and Kalman filters [33], [34] and considering that once its parameter has been properly selected based on the characteristic of the hardware and the specific motion under analysis, the MAD achieves accuracy comparable to the one of more complex filters. In this work, the MAD parameter value was set to 0.1 rad/s to appropriately balance the contributions of the accelerometer and gyroscope in estimating orientation. By assigning sufficient weight to the accelerometer, this

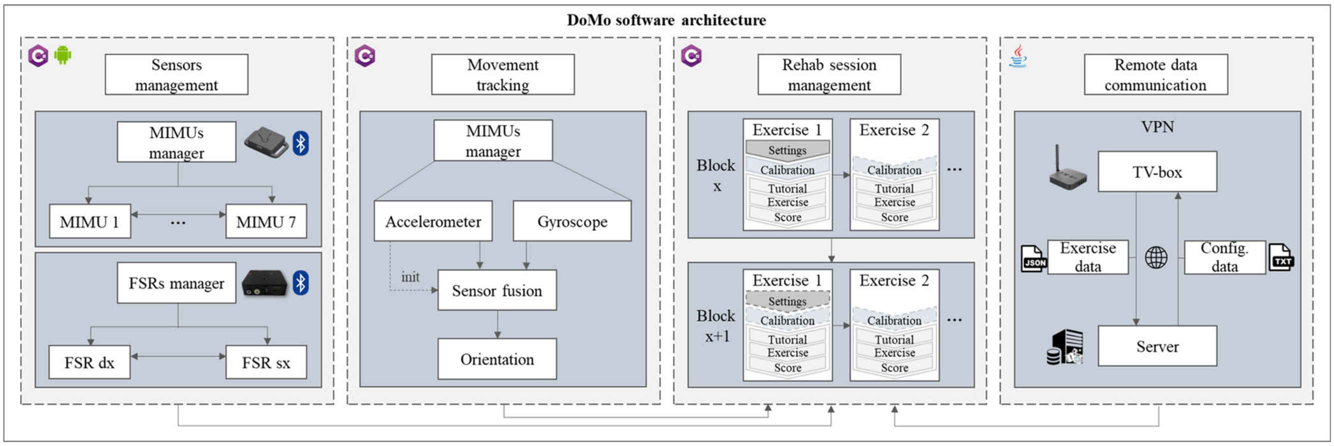

FIGURE 4. The DoMo software architecture is composed of four layers: sensors management, movement tracking, rehabilitation session management, and remote data communication. The programming language used for each block is shown in their top-left corners.

choice helps mitigate the drift introduced by the gyroscope, which can accumulate during acquisitions lasting up to a few minutes, while ensuring accurate gravity detection since the experiments do not involve significant external accelerations that could jeopardize it [35]. An algebraic quaternion, obtained by averaging the very first accelerometer values at the beginning of each recording with the subject still [22] and the segments oriented as much as possible in the zero-joint configuration (Table 2), was used to initialize the inclination of each MIMU and reduce the convergence time.

The MAD algorithm was executed without using a magnetometer to prevent orientation corruption caused by ferromagnetic disturbances, which are common in indoor environments. As a result, the MIMU-based orientation estimates lack a global common reference frame, except for the vertical axis defined by gravity. To overcome this limitation, the manual positioning of the sensors was leveraged to consistently align the GCS horizontal axes across all MIMUs [36], [37]. As expected, the accuracy of this approach directly depends on the accuracy of manual sensor positioning in matching the MIMU axes orientation in the zero-joint configuration (Table 2). Furthermore, the common GCS of the MIMU was defined to be aligned to that of the kinematic model.

After estimating the orientation of each MIMU separately, the quaternions are transferred to the TV-box via Bluetooth at 50 Hz. Then, the JCS of the specific joint under investigation is obtained by computing the relative orientation between the ACS of the distal MIMU with respect to the proximal one. The resulting quaternion is then decomposed into the triplet of Euler angles following the sequences listed in Table 2. The time series of the angle(s) of interest are then analyzed in real time, by means of C# custom-made routines, to count the number of repetitions, range of motion (ROM), execution time, and when required, also the movement direction (ascending or descending) based on the first derivative of the angle. All these quantities were used to provide real-time visual feedback to the patient to support the correct execution of the rehabilitation protocol, highlight incorrect movements, and prevent incorrect and potentially dangerous compensation strategies during training.

3) REHABILITATION SESSION MANAGEMENT LAYER

The rehabilitation session management layer (Fig. 4), which was developed in Unity3D and C# for Android, delivers the physical rehabilitation protocol to the patient in a semi-automated way. When the patient turns on the Android TV-box, the system automatically starts the specific sequence of exercises scheduled for that week of rehabilitation. In order to reduce the computational workload of the Android TV-box, the software architecture consists of a series of distinct applications, one for each exercise, plus several extras that are implemented to perform other procedures, including MIMUs configuration, the offset computation of their gyroscopes, and the anatomical calibration to align MIMUs to patient's segments. This approach increases the flexibility of the system for possible future integration of more exercises. At the end of each application, the next one is automatically started without any intervention by the user.

The rehabilitation session management layer has been designed to guide the patient during each step of the treatment. Each session has the same structure, consisting of several preliminary procedures and one or more blocks of exercises. When the system starts, the configuration application settings is executed. In this phase, the video interface illustrates how to switch on the sensors and checks the battery level of each MIMU. Then, the system starts the gyroscope offset removal, which is performed only once, at the beginning of each rehabilitation session. In case of low battery levels, the system notifies the user to charge the sensors; the application shuts down, and the session ends.

At the end of this procedure, the second application starts, and the system shortly provides instructions on how to wear

TABLE 1. Description of the anatomical coordinate system (ACS) for each segment and the corresponding identification method.

Body segment	ACS	Corresponding MIMU axis	Identification method
Trunk	Proximal - distal Antero - posterior Medio - lateral	x z y	Manual alignment + static
Arm (R/L)	Proximal - distal Antero - posterior Medio - lateral	-x / -x y / -y z / -z	Manual alignment
Forearm	Proximal - distal Antero - posterior Medio - lateral	-x -z y	Manual alignment
Hand	Proximal - distal Antero - posterior Medio - lateral	-x -z y	Manual alignment
Pelvis	Proximal - distal Antero - posterior Medio - lateral	x -z -y	Manual alignment + static
Thigh (R/L)	Proximal - distal Antero - posterior Medio - lateral	-x / -x y / -y z / -z	Manual alignment + static
Shank (R/L)	Proximal - distal Antero - posterior Medio - lateral	-x / -x y / -y z / -z	Manual alignment + static
Foot	Proximal - distal Antero - posterior Medio - lateral	z x -y	Manual alignment + static

In the ACS column, proximal-distal, antero-posterior, medio-lateral axes point upwards, forward, and to the right, respectively. For anatomical positioning, see Fig. 4.

TABLE 2. Details of the JCS, zero joint configuration and Euler decomposition sequence for each joint.

Joint	JCS	Zero joint configuration	Euler Seq.
Thorax-GCS	Flexion/Extension Lateral flexion R/L Axial rotation R/L	Thorax x,y,z axes coinciding with GCS z,x,y axes	YXZ
Shoulder (R/L)	Abduction/Adduction Flex/Extension Int/Ext rotation	Arm x,y,z axes coinciding with thorax -x, z,y/-x-z,-y axes	ZYX
Elbow (R/L)	Flexion/Extension Carrying Angle Prono/Supination	Forearm x,y,z axes coinciding with arm x,z,-y/x,-z,y axes	ZYX
Wrist (R/L)	Flexion/Extension Prono/Supination Radial/Ulnar deviation	Forearm/hand ACS coinciding	YXZ
Hip (R/L)	Flexion/Extension Abduction/Adduction Internal/External rotation	Thigh x,y,z axes coinciding with pelvis -x,-z,y/-x,z,-y	YZX
Knee (R/L)	Flexion/Extension Abduction/Adduction Internal/External rotation	Thigh/shank ACS coinciding	ZYX
Ankle (R/L)	Dorsiflex/Plantarflex Inversion/eversion Internal/external rotation	Foot x,y,z axes coinciding with y,-z,-x/-y,z,-x axes	ZYX

the sensors using the previously mentioned color code to indicate where each one has to be placed. As the maximum number of simultaneous BT communications reaches seven, the patient will be asked to reposition the sensors on the body between different blocks of exercises.

Remarkably, the rehabilitation session management layer can optimize the data sent by the sensors in accordance with the specific phase of the protocol. Moreover, it receives raw data from the sensor management layer, which are directly used or sent to the movement-tracking layer for interpretation. Sensor connection and data streaming are invoked upon request, so sensors are selectively activated according with the exercise to be executed, without any user intervention.

Once the users have positioned the sensors, they can press the OK button on the remote control of the TV-box to move to the next step, which is the subject-specific kinematic model calibration. This procedure is crucial to estimate the initial configuration of the sensors worn by the patient at the beginning of a block of exercises, and to obtain a clinically relevant kinematic reconstruction. It lasts less than one minute and has to be repeated before every new block.

After completing the preliminary stages, the system launches the application associated with the first exercise of the first block scheduled for the current session. At the end of each exercise, the rehabilitation session management layer launches the next one until the protocol of that week is completed.

4) REMOTE-DATA COMMUNICATION LAYER

This layer implements an Android service to manage data transfer from the TV-box to the remote server and vice-versa, as well as additional functionalities needed for the administration of the rehabilitation session. It has been developed by using the Android Studio IDE v. 3.4.1 and compatible SDKs 19 version, corresponding to Android 4.4 (KitKat) or higher.

The Android service starts automatically at the boot of the TV-box and works in background during the execution of the DoMo application. After booting, the service downloads the files from the remote server to customize the rehabilitation experience for the specific patient. These files contain clinical data of interests (e.g., residual motor skills and affected side), the identification code of the patient and the TV-box, and possible messages from the physiotherapist to the patient. All the files are locally saved in specific folders of the TV-box and used by the rehabilitation session management layer to correctly administer the therapy.

Subsequently, this service examines the TV-box folder where the rehabilitation session management layer saves all the files to be sent to the remote server. If the folder contains any new files, then the service sends them to the remote server through authenticated POST requests. This method has been preferred to continuous polling during exercise execution to reduce the TV-box workload. Afterward, the service reads the file reporting the starting date of the treatment (which is saved locally in the TV-box at the first operation of the system) and launches the first application scheduled for the current session, accordingly. All procedures performed by the Android service are completely transparent to the user.

A Virtual Private Network (VPN) has been integrated into the telemonitoring infrastructure to maximize the security of data transfer. This approach ensures that only authorized devices can access the DoMoMEA network. All DoMoMEA VPN-authorized devices are provided with an SSL protocol-based GPL License (Open VPN Community) certificate and open-source software (by YouAndTech srl, Italy).

5) EXERCISE INTERFACE

Each exercise is designed as a single application, which is composed of three main scenes: preliminary scene, main scene, and final scene.

The start-up screen scene shows the total number of rehabilitation sessions performed by the patient since the beginning of the treatment, and the total number of sessions defined in the protocol. Then, it presents a tutorial explaining the correct execution of each exercise through an animated avatar and a series of instructions, advice, and warnings.

The main scene allows the patient to perform the scheduled physical exercise. It is the only interactive scene of the whole sequence: the user interface changes in real-time in accordance with the data acquired from the sensors and processed by the movement tracking layer. Considering that the exercises defined in the protocol vary from one another and each one has specific features and requirements, the main scenes also differ significantly.

The final scene refers to the average performance obtained by the patient at the end of the exercise. The progress is shown with regard to the main parameters measured for the specific exercise (e.g., joint angles and execution time) both numerically and graphically. Furthermore, a final assessment enriched by some warnings and advice is presented.

In the main screen scene, the DoMo system provides both visual and audio feedback (i.e., written texts, color changes, and recorded voice messages) to inform about the quality of the movement accomplished by the patient. They are classified in three different categories based on their severity level: harmful behaviors, compensatory movements, and motivational.

Any feedback alerting on harmful behavior (such as hyperextension of a joint) has the highest priority, and it is always presented to the patient. In addition, any feedback concerning compensatory movements (which are less severe) is still recorded, but it is issued to the patient only if no harmful behavior occurs. Finally, motivational feedback (characterized by the lowest priority) stimulates the patient every three repetitions only if no higher-priority feedback showed up during that repetition.

The complexity of the virtual scenario is different among exercises in order to assess and compare the potential benefits of essential visual feedback interfaces and exergame interfaces in a telerehabilitation context, by balancing patient's engagement and compliance with the cognitive load determined by gamified virtual scenarios [32], [33].

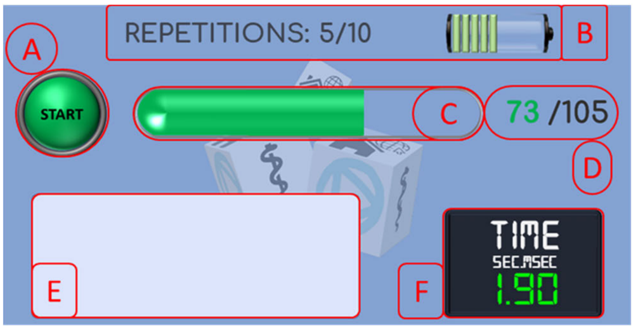

FIGURE 5. Example of a visual feedback interface.

Except for some minor differences depending on the peculiarities of each exercise, all visual feedback interfaces have similar structures. Their essential design aims to provide all the information the patient needs to carry out the rehabilitation session without unnecessary, and possibly distracting, elements. Figure 5 depicts an example of visual feedback interface, where the main performance variable of interest is represented in a filling bar (C); in this case, the filling amount is proportional to the amplitude of the estimated value (e.g., a joint angle), and it is colored in green until the patient stays within the safety range for that movement; otherwise, it turns red, indicating a harmful situation. The numerical value (D) on the right end of the bar indicates the actual value of the measured parameter with regard to the expected maximum value. A round sign (A) marks the beginning of a new repetition: if the sign is red, then the patient has to wait for a new repetition to begin (i.e., when the sign turns green). The number of correctly executed repetitions with regard to the total number of repetitions to be performed is shown numerically and graphically in the upper part of the interface (B). The execution time of each repetition is reported on the panel in the bottom-right corner of the screen (F), whereas another panel displays motivational or warning messages in the bottom left corner (E).

Figure 6 shows an exergame interface for a trunk lateral flexion exercise. During the exercise, the patients sit on a chair in front of a rigid and stable surface (e.g., a table),

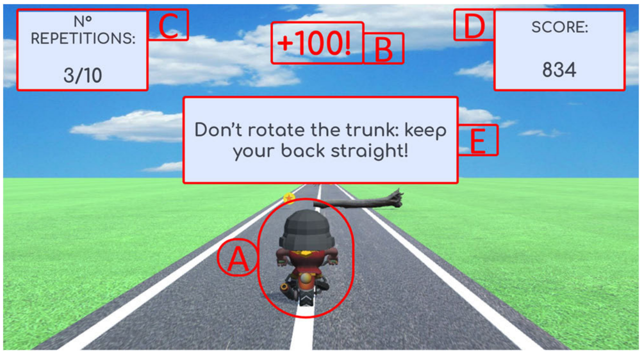

FIGURE 6. Example of an exergame interface.

and they must flex the trunk alternatively to the left or right to avoid a series of obstacles occurring on a virtual street. In the center of the interface, an avatar in the form of a biker (A) rides along the street reproducing patients' movements in real time in accordance with the data acquired by MIMUs: when the patient flexes the trunk, the avatar moves accordingly, and the wider the RoM of the flexion movement, the more the biker moves. For each correctly executed repetition, an algorithm computes a score (B) based on the values of the measured parameters (RoM and execution time). When a virtual obstacle occurs on the road, if patients do not flex enough the trunk, they will collide with the obstacle obtaining a penalty. On the upper side of the interface, the repetition counter panel (C) and score panel (D) are reported. Motivational or warning messages are shown on a popup panel (E). Both scores and motivational feedback are tuned in accordance with patient's needs and residual motor and neuropsychological capabilities, assessed by a physiotherapist through a dedicated examination before the beginning of the treatment. It is worth noting that they can be modified during the rehabilitation program (not during training) by the physiotherapist based on patient's progresses, thereby ensuring a challenging workout with reachable targets and feasible movements.

C. TELEMEDICINE FRAMEWORK

The telemedicine framework leverages on three main components: the DoMo system, the remote server, and the web app for data access. The DoMoMEA server collects the data of interest coming from all DoMo devices assigned to the patients, making them accessible through a dedicated web application.

1) REMOTE SERVER

A Linux Ubuntu 20.04 LTS Server virtual machine (featuring 4 VCPUs, 8 GB Ram, and 160 GB HDD) is used as the remote server, which is provided by YouAndTech srl, Italy. It has a PostgreSQL 10.16 database, which provides excellent robustness, scalability, and responsiveness.

The database consists of six main entities: User, Exercise, Game, Minix, Motor skills, and Message. The User entity has three children: Patient, Physiotherapist, and Staff. Each child entity has different rights, granting access to different kinds of data based on the user's role.

All files of clinical or scientific interest associated with the rehabilitation sessions are saved locally in a specific folder of the Android host at the end of each session and securely sent via HTTPS posts to the web server at the next start of the Android host. These files are eventually deleted from the Android device after being correctly sent. On the server side, files containing messages for the patient, configuration information, and clinical data are processed by Python scripts and loaded onto the database. All files are identified by a unique device–patient identifier, and the association between patient and device can only be requested by querying the database on the server to keep the files anonymous. Validations on the received data are performed in the Python back-end, and if any inconsistencies are detected, then specific alerts are sent to the system administrators by email. Most of the functions compile a log file on the server; thus, the administrators can always check the actions performed in the web app.

The redirection and organization of all the information are managed in Python language using the Django framework. The client–server connection includes the following files: the configuration file (JSON), with any messages for the patient (txt) from the server to the client, and a file for each exercise performed (JSON) from the client to the server. Django, which is used in multi-tier architectures, follows a model–view-template pattern. The model includes data models of object classes and provides a representation for database tables; the templates are html files that represent the web app pages: they have a html base that can be enriched with other languages (CSS, JavaScript, etc.), while views (the controller part of the MVC pattern) are Python functions that manage page visualization and the back end. The input data to the server is accepted by the NGINX web server. Based on the security approach followed in the design, data transfer occurs over a VPN (II.B.4). Therefore, the OpenVPN app has been installed on each device and configured on a VPN (by YouAndTech srl).

2) WEB APP

The web application has been developed using the Django framework and Python 3.7 through HTML 5, CSS, and JavaScript languages. After logging in, the system automatically recognizes the user class based on specific attributes and redirects directly to the reserved area. Each class of users can access a different reserved area integrating different functionalities. New staff users can only be instantiated by administrators.

The staff is responsible for users' registration and technical management of treatments. In particular, it is allowed to create new physiotherapist and patient users, insert and modify their personal data, visualize users lists, associate a patient to a certain physiotherapist, and assign them to an Android host.

Physiotherapists visualize the list of their patients to manage their therapy, set and change their motor skills (Fig. 7),

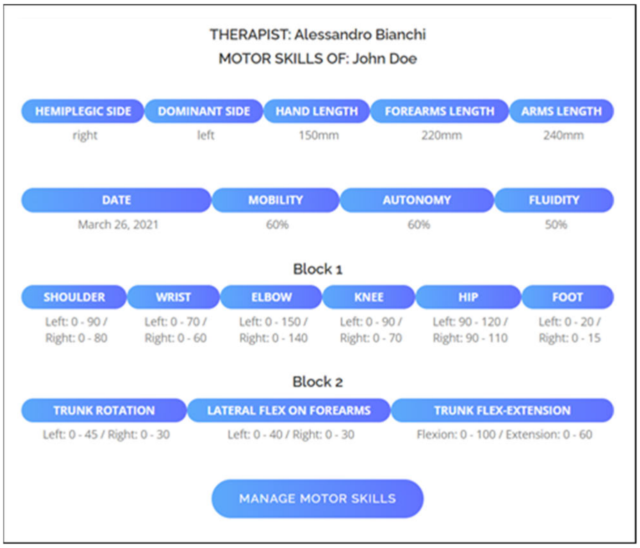

FIGURE 7. Example of motor skills page in therapist's protected area.

send messages to the Android host, and visualize different information: a progress table comparing patient's performance to those of a healthy subject, the list of exercises performed by the patient (possibly filtering by type or date), and the main parameters of assessment for all exercises in tabular or graphical form (Fig. 8).

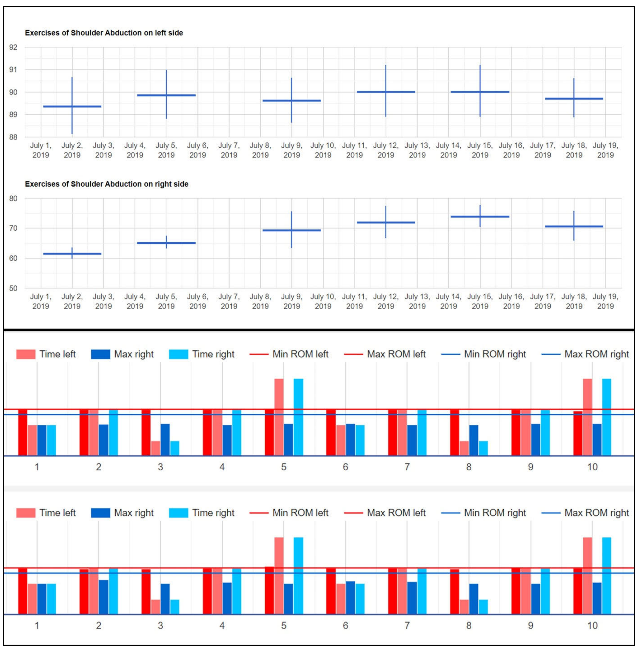

FIGURE 8. Web application. Example of graphs the therapists visualize in their reserved area: weekly report (up) and exercise detail (down).

Django NumPy and import–export libraries were used for statistical calculations of data and data export in CSV files, respectively; all web app charts were created with Google Charts through JavaScript snippets that use online libraries (https://www.gstatic.com/charts/loader.js). Moreover, an alert reports a prolonged inactivity (4 days or more) ensuring physiotherapists' full control over the whole rehabilitation process. Finally, patients can see the list of exercises similar to the physiotherapist but, in this case, the graphs are simplified for an easier interpretation.

III. RESULTS

A. USABILITY TESTING ON HEALTHY VOLUNTEERS

The DoMoMEA system was preliminary tested for usability on 11 healthy elderly volunteers (69 ± 5 years old), with low computer literacy and with no previous experience with similar technologies. The study was performed following the principles outlined in the Helsinki Declaration of 1975, as revised in 2000. The study was approved by the Ethics Committee of the University of Cagliari (prot. n. 2025-UNCACLE-0057832). No personal data was collected. The testing session was conducted in three subsequent phases:

1. preliminary phase: participants and their family members received information about the DoMoMEA system, its purposes, and functioning;

2. interactive phase: the participant started a rehabilitation session consisting of three exercises selected from the clinical protocol (i.e., SAA, TR, and TFE) following the instructions provided by the user interface only;

3. assessment phase: participants evaluated their usability experience of the proposed system by filling in the questionnaire of the System Usability Scale (SUS) [34], [35], and indicating their feedback and satisfaction level.

The SUS is a universally accepted tool for reliability, ease of use and interpretation, and allows to quantitatively compare the results obtained by different solutions aimed at solving similar issues. Remarkably, participants were not trained on the use of the platform in the preliminary phase, and only the functionality of the different system components was described. In this way, it was possible to determine how much the system was perceived as user-friendly by a general target of unaffected elderly participants, and its real capability to guide the patient through the different phases of the rehabilitation session. The average value of SUS score was 82 ± 6 points, thus considerably above the accepted average value (68/100), indicating an excellent level of usability [36]. Nevertheless, this test revealed that some participants felt the need to be assisted by a skilled person during the use of the DoMoMEA system.

According to the 63.7% of volunteers, training with exergame interfaces was preferable, whereas 36.6% of volunteers felt amused by the exercise that requires more active movements, regardless of whether a visual feedback interface or exergame interface was used. All volunteers appreciated the presence of feedback provided by the system about their performance, both at each repetition and at the end of the exercise, when further advice was provided.

B. SEMI-STRUCTURED INTERVIEW WITH CLINICIANS

In order to obtain feedback on the features and relevance of the proposed system for telerehabilitation of stroke patients, a semi-structured interview was administered to physiatrists and physiotherapists (questions are reported in the Supplementary Material, SM). By an on-line form encompassing both multiple-choice and open questions, also including two descriptive videos of the system and the telemedicine infrastructure, the interview collected information regarding demographic information (questions 1-4, see SM), clinical experts' approach to daily routine (questions 5-23), their perception of the proposed DoMoMEA system (questions 24-34), and its actual applicability in the clinical practice (questions 35-37). The experts were interviewed on the impact of the use of the proposed system in their clinical practice and were asked to provide possible suggestions for improving it.

1) DEMOGRAPHIC INFORMATION

The interview lasted about 30 min on average. Thanks to the support of the Sardinian chapter of the Italian society for physical and rehabilitation medicine (SIMFER), 23 clinicians (7 physiatrists and 16 physiotherapists) participated on a voluntary and anonymous basis. Their demographic information (see questions 1, 3, 4) is reported in Fig. 9.

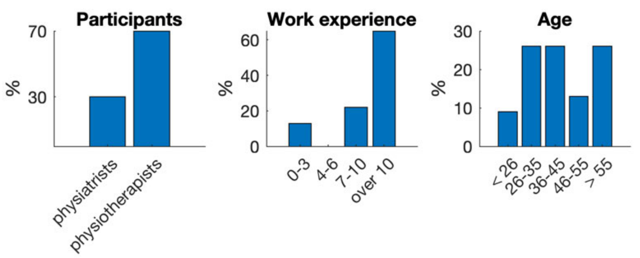

FIGURE 9. Demographic information on the population of clinicians participating in the semi-structured interview. Of these, 65% are over 35 years old; 65% have more than 10 years of work experience, while 13% have less than 4 years of work experience.

2) CLINICAL EXPERTS' APPROACH TO DAILY ROUTINE

About one half of the clinicians (52%) stated that they work in a private clinic, while 65% of them carries out both in-hospital and home assistance, and 40% have further specialization in rehabilitation. Regarding the experience in the context of scientific research, 39% collaborated in research projects, but only half of them have been involved in projects dealing with the development or testing of prototypes for rehabilitation.

Furthermore, 78% of the clinicians who participated in this survey are used to assist post-stroke patients. However, only a third of them dedicate more than 40% of their working time to caring for such patients, while the remaining majority mostly take care of patients suffering from other pathologies with neuromotor symptoms similar to those of stroke. Remarkably, 75% of clinicians claimed the necessity of real-time monitoring of patients during their home-based rehabilitation. The remaining experts perceived real-time monitoring as a critical need only for some patients (based on the type of patients, their autonomy and ability to self-manage, as well as the unrecovered impairments caused by stroke) and the possible presence of a caregiver during home rehabilitation. In any case, for most of the responders (75%), it is important to frequently monitor the rehabilitation data/parameters of their patients when the exercises are performed at home without expert supervision, while the others believe that the monitoring frequency should be personalized depending on the clinical characteristics of the patient.

Similar trends are also observed when assessing the usefulness of a system allowing for the automatic collection of rehabilitation data/parameters of post-stroke patients in home settings, for their remote (a) synchronous analysis by the specialist. Remarkably, the interview revealed that 70% of clinicians believe that this solution can provide a value added in general, because it would allow for objective data, enabling an informed modification of the rehabilitation protocol based on the patient's real needs and progress, while the others think that it depends on the type of patients (i.e., it would be valid for those patients with very low cognitive impairment, good sensorimotor control, good static-dynamic balance, and able to recognize alterations in their movement associated with motor training). Most experts (70%) are convinced that patients could benefit from automatic feedback on their performance during home rehabilitation sessions.

3) CLINICAL EXPERTS' PERCEPTION OF THE PROPOSED DOMOMEA SYSTEM

Clinicians were then asked to watch a short video presentation of the DoMoMEA system (https://www.youtube.com/watch?v=J9K0dKPyXq0). From the experts' comments, it emerged that the system was found very interesting and with a good usability even for daily practice. Interestingly, the approach was considered innovative and engaging for the patient, and the technology was perceived as suitable for the purpose. Furthermore, the system was seen as a complementary and crucial element to traditional rehabilitation, allowing for remote rehabilitation sessions supplemented by multimodal feedback even in out-of-hospital environments that are not necessarily domestic (e.g., physical rehabilitation centers).

Among the strengths of the system, clinicians have particularly appreciated the simplicity of use, portability, ease of installation, the possibility of monitoring the outcomes of the rehabilitation training remotely, and the automatic online control of the correct execution of the motor gesture. At the same time, however, some limitations of the system have been highlighted: the device must be applied to patients with specific motor and cognitive characteristics and the protocol must be customized according to the patient's needs (30%); the exercises are considered quite generic and limited to the body vertical position, with the possibility of excessive compensation of the healthy side (4%); the positioning of the sensors necessarily requires the presence of a caregiver (17%). Moreover, the system does not allow to visually control of the patients during the training with a raw video (4%), beyond the recorded kinematic data. Remarkably, 78% of experts consider DoMoMEA as a low-cost telerehabilitatiom system (approximately 1900 Euros for the small production of the research project, as detailed in the next section).

Some experts (22%) would prefer a real-time system, because it allows the clinician to correct any compensatory movement that otherwise might not be detected by the system, even though the store-and-forward approach could be valuable for advanced stages of rehabilitation or in certain categories of patients. As regards the remote monitoring, the web interface of the telemedicine platform was perceived as simple and complete by most experts (70%), although less intuitive for patients, but still complete and adequate for the purpose. All but one clinician appreciates the fact that the patient has access to their data, whereas half of them considered the embedded messaging service useful.

4) ACTUAL APPLICABILITY OF THE DOMOMEA SYSTEM IN THE CLINICAL PRACTICE

Anyway, all experts agree that the physiotherapist should monitor patient data remotely, possibly together with the entire rehabilitation team (43%), and that the proposed paradigm is compatible with current normal clinical practice, although their current work organization needs to be changed. The system was also considered beneficial (87%) for other pathologies other than stroke, provided that the experimental protocol is adapted, while 70% of participants would like to try the DoMoMEA system with their patients.

IV. DISCUSSION

DoMoMEA provides a set of features uncommon to the commercial or research devices with similar functions and performances [11], [37]. First of all, it provides a full-body rehabilitation treatment that can be customized by the physiotherapist, which frees the patient from the use of other devices for the treatment of specific parts of the body (upper or lower limbs, trunk, etc. [17], [25], [26], [27]) and allows the clinician to optimize the treatment taking into account all residual motor skills and recovery needs of the patients, as well as their progress evaluated during training sessions. These features are essential for post-stroke neuromotor rehabilitation, but they are also easily applicable to other neurological disorders (e.g., Parkinson's disease, ataxia, etc.), chronic trauma, rheumatism, low-back pain, and others.

Furthermore, to provide remote patient monitoring, the system is equipped with a store-and-forward telemedicine platform, which provides scalability and allows the physiotherapist to evaluate the at-home rehabilitation sessions carried out by a large number of patients day by day. In such technology, the clinician can also send messages to the patients via the same platform. Supervision by an informal caregiver in the initial setting of the system is needed for the patients with reduced mobility [7], [8].

In terms of sensor technology, after a preliminary analysis of the pros and cons associated with the different motion capture technologies, the IMU technology was selected on the basis of other existing post-stroke rehabilitation solutions. A relevant alternative technology is also represented by RGB-D cameras, particularly the Microsoft Kinect device and other similar devices like Microsoft Azure Kinect DK and Orbbec Femto Mega. In general, cameras can be easily used by patients, and they require a minor integration effort because of the built-in software tools, but their performance can be significantly affected by environmental conditions, which can cause discontinuous tracking because of optical occlusion and illumination issues. Moreover, RGB-D technology hampers the possibility to help and manually guide the patient during movement execution, and it cannot be made portable easily. Nonetheless, despite requiring complex software management, IMUs provide optimal functioning regardless of the environmental condition; thus, they are suitable for unsupervised home-based rehabilitation. Finally, given the selected hardware platform, the system could be integrated as a service in other Android-based telemedicine and tele-care solutions.

Remarkably, the choice of FSRs in DoMoMEA is currently unique in the home-rehabilitation scenario: this aspect is valuable because of their low cost, versatility, customizability in shape and possibility of being integrated into clothing and devices, thus offering reliable and accurate measurements for the system's intended application.

Another significant aspect of any tele-rehabilitation system is its sustainability. In fact, the proposed DoMoMEA framework is designed as a low-cost system, especially when compared to currently available complex commercial and research systems with similar performance. At the time of writing, the cost of a complete DoMo kit is approximately €1900, including the mini-PC (€150), seven IMUs (€1024), commercial insoles with encapsulated FSR sensors (€740), and the FSR readout electronics (€195). These costs can be dramatically reduced with larger production.

Finally, the clinical feedback highlighted the potentialities of the DoMoMEA solution in its prototypical version, as well as possible improvements. In fact, the clinicians argued about the absence of exercise performed while laying on a bed, which however can be easily included thanks to the adoption of the IMU technology. A live-streaming video channel for physiotherapists was highlighted as a possible improvement too, which can be surely integrated as a complementary issue, along with a video recording session, without affecting the measurement features, real-time feedback, and integrated rehabilitation support.

V. CONCLUSION

In this work, the prototype of the DoMoMEA telerehabilitation system for the full-body neuromotor rehabilitation of post-stroke patients with mild impairment is presented with detailed information about its software and hardware architecture. The results of the usability test administered to healthy participants show the excellent usability of the system, perceived as easy to use with a user-friendly interface, although requiring additional assistance by caregivers in some circumstances, e.g. during anatomical calibration to align MIMUs to patient's segments. On the other hand, the outcome of the semi-structured interview to clinicians confirmed the interest of clinicians towards the DoMoMEA system, motivated by clear advantages such as ease of use, versatility of the system, the possibility of correcting patients' movements in real time through multimodal feedback, the possibility of monitoring a large amount of objective data remotely by the clinical team, and possibly extending its application to other pathologies with neuromotor symptoms similar to those of stroke.

As the next step, the DoMoMEA system, currently tested on healthy but age-matched participants as a preliminary stage, is going to be validated in a clinical trial involving 40 stroke patients with mild impairment, which will perform the home rehabilitation. Inclusion criteria will be: age (40-75), first cerebral stroke affecting the left side of the brain (within 6 months from the acute event) and autonomy in walking. Exclusion criteria will be: cognitive impairment (MMSE<24), cardiac instability, respiratory instability, neurodegenerative disorders, systemic diseases. This phase will also be important to evaluate the system's usability on the target population (post-stroke participants). The limitations highlighted by the interviews with the experts, such as the small number of exercises, absence of video recording or real-time video channel for the physiotherapist, will be considered for the future development of the system.

Moreover, the evaluation of new applications of the system is underway, taking into consideration its versatility and the modular design of its software architecture. All conditions where passive exercise is required, even if assisted by informal caregivers, can benefit from the adoption of such a wearable technology embedding exergaming approaches.

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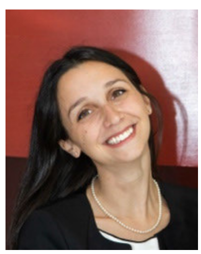

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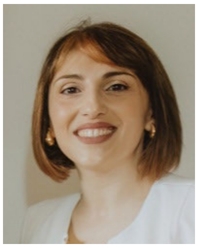

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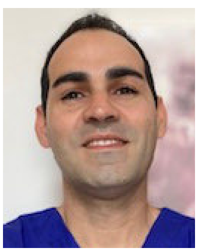

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