Serious Games and In-Cloud Data Analytics for the Virtualization and Personalization of Rehabilitation Treatments

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***Abstract*—During the last years, the significant increase in the number of patients in need of rehabilitation has generated an unsustainable economic impact on healthcare systems, implying a reduction in therapeutic supervision and support for each patient. To address this problem, this paper proposes a telerehabilitation system based on serious games and in-cloud data analytics services, in accordance with Industry 4.0 design principles regarding modularity, service orientation, decentralization, virtualization, and real-time capability. The system, specialized for poststroke patients, comprises components for real-time acquisition of patient's motor data and a decision support service for their analysis. Raw data, reports, and recommendations are made available on the cloud to clinical operators to remotely assess rehabilitation outcomes and dynamically improve therapies. Furthermore, the results of a pilot study on the clinical impact deriving from the adoption of the proposed solution, and of a qualitative analysis about its acceptance, are presented and discussed.**

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***Index Terms*—Data analytics, decision support systems (DSS), neuromotor rehabilitation, serious games, telerehabilitation.**

I. INTRODUCTION

THE significant increase in the number of patients in need of rehabilitation has generated an unsustainable economic impact on healthcare systems, implying a reduction in the amount of therapeutic supervision and support for each patient. This is particularly true for poststroke patients [1]. Stroke afflicts about two million people every year in Europe and is the leading cause of serious, long-term adult disability worldwide [2]. It affects brain activity leading to deficits in motor and cognitive functions, at least for a certain time, thus, negatively impacting on the patient's ability to perform daily activities. Inpatient rehabilitation programs guided by therapists are the primary means to address and improve impaired motor and cognitive functioning caused by a stroke [3]. However, poststroke patients do not completely recover their original functional level for different reasons, e.g., stroke severity, lack of motivation to perform rehabilitative exercises, or insufficient, and/or nonoptimal training in the initial weeks following the stroke. Unfortunately, only a limited number of individuals with residual deficits in functioning receive outpatient rehabilitation due to inadequate health service funding [4]. This is extremely disappointing since, in the opinion of many therapists, the number of inpatient rehabilitation exercises is generally insufficient and the lack of regularity of outpatient rehabilitation exercises prevents improvements from being completely effective [5].

In the last few years, telerehabilitation systems have been proposed as a very promising solution to support and motivate poststroke patients in the performance of rehabilitation exercises at their own home, with only limited, or even without, human supervision. In addition, systematic reviews and clinical trial data have shown that serious games can be used to improve motor rehabilitation in poststroke patients for a range of functional deficits [6], while increasing patient engagement [7]. Nonetheless, some factors currently limit the adoption of game-based stroke rehabilitation in real scenarios [8], [9], including the following:

1) expensiveness, invasiveness, and nonportability into the home setting;
2) impossibility of customizing the therapy for the specific patient;
3) excessive complexity and therefore unsuitability to be used by nontechnical therapists and lack of attractiveness for the patients;
4) lack of automatic, adaptive methods in requesting prompt intervention of therapists, in order to limit frustration and abandonment and increase motivation and engagement.

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This paper proposes, as main contribution, a poststroke telerehabilitation system based on serious games and in-cloud data analytics services. The system exhibits its novelty in the way that it provides an extensive set of features addressing all the above mentioned limitations and devised in accordance with some of the design principles, namely, modularity, service orientation, decentralization, virtualization, and real-time capability, identified in [10] with reference to the Industry 4.0, and still valid for the health scenario here considered. In detail, the proposed system integrates a set of neuromotor and neurocognitive serious games, based on low-cost and uncumbersome sensing devices, able to adapt to different stroke-related functional impairments (modularity), in order to collect data and enhance the patient's engagement. Moreover, it integrates decision support facilities, arranged as cloud services that can be delivered and reached anywhere, anyhow and at any time (service orientation), able to approximate medical expertise and human-like reasoning capabilities, in order to remotely analyze the collected data and support therapists in refining patients' daily exercises (decentralization). The whole system is able to operate in near real time (real-time capability), allowing for delivery of a patient-centric model of care, where therapists are not obliged to be physically present at the patient's home, but they are automatically aided in providing personalized indications or feedbacks about patient's therapy exercises in a virtualized manner (virtualization).

II. RELATED WORK

In this section, different rehabilitation systems and frameworks have been analyzed and compared to the proposed system according to a set of requirements, which were identified by the doctors and therapists involved in the pilot study as needed for use in real scenarios:

1) customizable therapy;
2) patient engagement;
3) expensiveness, invasiveness and nonportability;
4) reduced human supervision;
5) automated exercise monitoring and analysis;
6) extendibility of the serious game environment.

For each requirement, the original contribution of the proposed system has been described by highlighting the main differences with the other approaches.

The first requirement is the capability of offering a functionality for the customizing of the therapy for specific patients and specific rehabilitation targets. While the works [11]–[13] completely support this requirement for therapy customization, others, namely [14]–[19], [19]–[24] offer only limited and partial mechanisms to tailor the exercises for individual patients. In this respect, the proposed system provides the therapists, with little to no programming skills, with a user-friendly interface that allows the definition of exercises tailored to the needs of specific patients.

Second, the therapists emphasized the need to enhance the patients' engagement through gaming. In fact, scientific evidence suggests that when a patient focuses on the game rather than her/his impairment, the exercise becomes more enjoyable and is more likely to be maintained over the many sessions needed to induce a gain in motor functioning [25]. This aspect proves to be almost totally supported in all the works examined. The proposed system, in addition to enhancing the patient's engagement through gaming, further involves the patients by focusing on rewarding cognitive exercises while simultaneously enhancing motor functions. This choice is justified by the fact that studies in literature have shown that presenting the patient with a motivating and distracting cognitive challenge can facilitate the engagement with the serious game [26], by reducing the possibility of any abandonment of the therapy due to depression and frustration generated by the stroke trauma and the extended period of recovery.

The need of space and cost minimization was also highlighted and considered worthy of analysis. Some of the works are based on uncumbersome and low cost devices that can be easily used in home settings [22]–[24], whereas all the others require more complex set-ups. In this respect, the proposed system is based on low cost and on the shelf devices easily transportable and installable into the home, providing an expedient and practical mode of ongoing care.

Furthermore, the therapists requested the possibility for the patient to perform the rehabilitation program independently, so requiring a less direct involvement from the medical staff. While the works [12], [13], [15]–[17], [20], [22], [24] respect this requirement, others, namely, [11], [18], [21], offer only a limited set of functionalities to minimize the involvement of the therapist in patient's daily rehabilitation. The proposed solution offers to the patient the possibility of performing, on a regular basis, rehabilitation programs independently and quietly at home in a family context, without the need for the continuous presence of therapists. Indeed, the amount of feedback given by the system on the execution of the rehabilitation exercises allows for less direct involvement from the therapists and a greater awareness on the part of the patient.

Another important requirement highlighted by the therapists is the capability of an automatic monitoring of the exercises assigned to the patients in order to, on the one hand, draw up and complete a daily report about the state of the therapy and, on the other, to automatically analyze and correlate the collected results. In this respect, while some works [11], [12], [20] offer both a monitoring and automatic analysis of patient progress and performance, some others [13], [19], [21]–[23], instead, provide only the monitoring functionality. The works [16], [17] are mainly focused on the evaluation of patient performance only. Compared to relevant literature, the proposed system is able to automatically monitor the patient's exercises, also providing the therapist with a complete and detailed daily report, so improving knowledge on the patient's rehabilitation progress. In more detail, it is able to analyze and correlate the results of each daily exercise session, quantitatively and qualitatively reason on them by encoding medical expertise and, finally, notifying the therapists about any encouraging or poor motor, cognitive or psychological improvements obtained by the patients. Depending on these outcomes, it can suggest to the therapists some adjustments to the daily therapy program for the patients in order to avoid their frustration and abandonment, in the case of

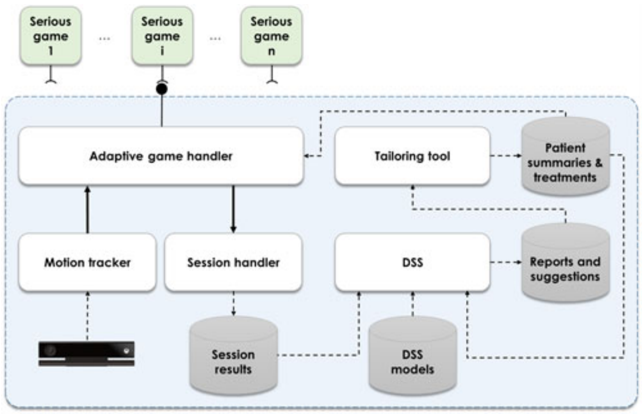

Fig. 1. High-level system architecture.

poor results, or to reinforce their engagement and awareness, in the case of encouraging improvements.

Finally, a further requirement arises with respect to the need to support an easy extension of available serious games, in order to make the device itself a more appealing solution for therapists and patients. However, none of the considered works provides seamless integration mechanisms to access the suite of serious games on offer while, in the proposed solution, new serious games can be easily added to the suite if they are developed in a manner consistent with the interface proposed by the system.

III. SMART TELEREHABILITATION SYSTEM

A. System Architecture

As shown in Fig. 1, the system is organized in different components. Due to real-time constraints, the components interacting with depth sensors, namely, the *adaptive game handler*, the *motion tracker* and the *session handler*, and all the *serious games*, are deployed locally. The other components, namely, the *tailoring tool* and the *Decision support system (DSS)*, are available as web services hosted on a private cloud to be accessed remotely by therapists and medical experts. The choice of a private cloud is due to the need of keeping a direct control over where sensitive data resides and who can access them. Thus, all the data are safely memorized in storage repositories of the private cloud, enabling efficient retrieval, updates and quick transfers as and when required, in accordance with the proper authorization rights.

Each *serious game* exposes a common interface, which includes, as input, *level of difficulty*, *pointing* and *selection* features and, as output, *total score* and *execution time*.

The *adaptive game handler* is in charge of decoupling the serious games from the *motion tracker*, which tracks the patient's movements by using the Microsoft Kinect v2 sensor. It can map from one to three user movements to the serious game logic, by connecting the received tracking data to the serious game pointing and selection actions. Thanks to this component, new serious games can be easily connected to the system if they conform to the common interface. All the session data produced by both the motion tracker and the serious games will be sent and handled by the *session handler*, which is in charge of storing them into the *session results* repository.

The *tailoring tool* is the primary point of access for the therapist, where she/he can specify the patient summary and the rehabilitation goals. These latter are expressed as a list of objectives for each motor district, characterized by the anatomical problem of interest (e.g., left shoulder abduction or right leg flexion), the initial range of motion (ROM) the subject is able to perform, and the target ROM the therapist desires to reach. All this information is stored in the *patient summaries and treatments* repository. Moreover, this component is used by the therapist to visualize the daily report of the patient's activities and the suggestions for improvements in the customization of the therapy. This information is automatically generated by the *DSS*, by employing knowledge-based models contained in a local store named the *DSS model*, and successively memorized in the *report and suggestions* repository.

The tailoring tool and the DSS are developed and deployed as three-tier Software as a Service web applications that make use of Apache at the web server tier, Tomcat at the application tier with MySQL as the database server. They are both wrapped into a set of service components according to the web service resource framework standards and deployed on a private Infrastructure as a Service cloud built by using OpenNebula.

Further details on the adaptive game handler and on the DSS are provided in the following sections.

B. Adaptive Game Handler

The adaptive game handler accesses the patient treatment as recorded by the therapist. Such an initial configuration should contain, for each serious game included in the patient therapy, the following information:

1) at least one but no more than two physical exercises to perform (abductions, extensions, etc.) with the indication of the involved motor district to track;
2) for each motor district, the ROM in which the patient should exercise;
3) for each serious game, the selection technique (wait-to-click, with an indication of the trigger time, or grabbing);
4) for each serious game, its level of difficulty.

By using such configuration data, the component can filter the patient's joint data provided by the motion tracker, computing the angles only on those motor districts selected by the therapist.

Pointing can be performed by using either two items of input data (e.g., (x, y)) or a single one (e.g., p, defining the position of the pointer in a fixed path that covers all the game objects). All the pointing data are normalized in $[0, 1]$ by using the ROM configuration set by the therapist. They are further smoothed by means of a velocity-based filter [27]. Motion data outside the active interval are pruned before being sent to the serious game. However, they will be sent to the session handler to enable further analyses. For the selection task, two different interaction techniques can be used: *wait-to-click*, in which the patient has to maintain the pointer over the selected object for an amount of time, defined by the therapist, to confirm the selection; and *grabbing*, which requires the patient to close her/his hand in a fist to confirm the selection. The selection values are 0 or 1.

Relevant data are sent to the session handler. Such data include the following:

1) the maximum axis-angles performed by the patient in the assigned exercises;
2) the minimum axis-angles performed by the patient in the assigned exercises;
3) the game score;
4) the execution time.

C. Decision Support Service

This service is in charge of automatically integrating, analyzing, and correlating, for each patient, the results of each daily exercise session with information pertaining her/his profile and treatment plan, reasoning on them by approximating medical expertise and human-like reasoning capabilities, and finally, generating a complete and rich daily report, where motor improvements are highlighted and some possible adjustments to the daily patients' treatment are suggested.

From a more technical perspective, the DSS essentially relies on hybrid production rules built on the top of ontological and fuzzy primitives and on the inference engine proposed in [28] to reason on them in order to obtain transparent, qualitative and interpretable insights, and suggestions. Each rule is expressed in the form "*if premises then decision option,*" where a single *condition* corresponds to a datum collected during the patient's exercise or extracted from her/his summary or treatment plan, whereas a *decision option* is an indication about hopeful or unsatisfactory treatment results or a suggestion about some possible treatment adjustments.

In detail, on the one hand, ontologies have been used to represent both the information handled by the telerehabilitation system and the medical knowledge possessed by the professionals involved in the rehabilitation process. This whole set of information and knowledge has been elicited and modeled, with the cooperation of engineers, doctors, and therapists, in terms of concepts, properties, and relationships by exploiting a shared vocabulary, so as to grant fundamental characteristics of being formal, semantically well-defined and interpretable. All this domain knowledge has been coded in the form <*subject, predicate, object*>, according to the *N*-triples syntax [29]. The main concepts of the ontology are shown in Fig. 2.

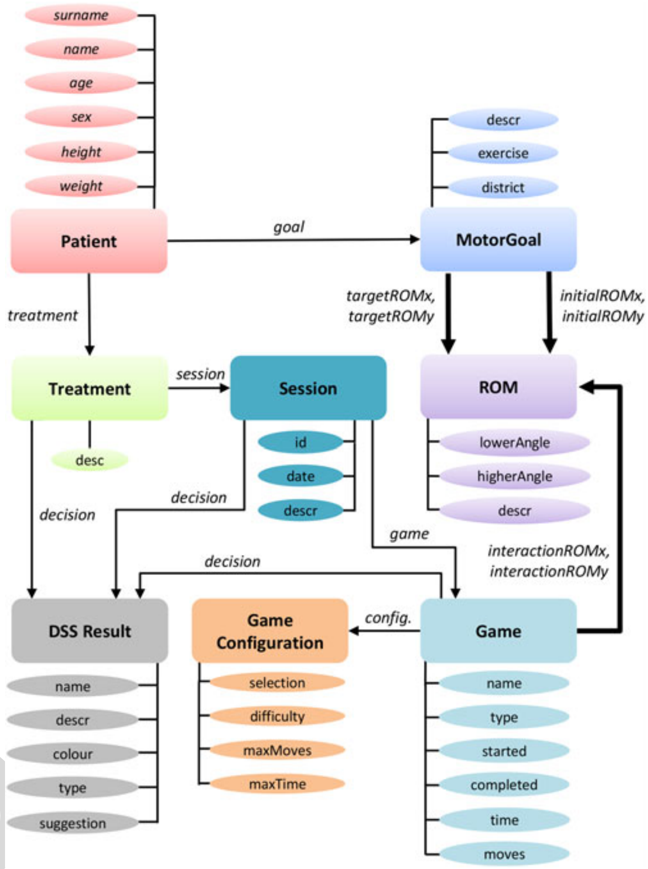

Fig. 2. Ontology model for describing the domain of interest.

Fuzzy logic, on the other hand, has been adopted to model qualitative knowledge in the form of fuzzy variables assuming, as values, linguistic terms, such as low, medium, and high. These linguistic terms have been elicited and modeled, also in this case with the cooperation of engineers, doctors, and therapists, in the form of smooth sets of values, with a membership degree defined in a continuous range of truthvalues between 0 and 1. Such a way, medical knowledge owned by doctors and therapists has been represented more realistically, since it abounds of graded and qualitative formulations in place of precise thresholds representing oversimplifications of the reality. All the hybrid production rules have been encoded by using ontological concepts and properties to express quantitative information as well as fuzzy variables and linguistic terms to represent qualitative information. In particular, three different sets of hybrid production rules have been arranged, which take into account data produced by the single game, collected daily within a session or collected during different consecutive sessions.

The first set of rules operates at game level in order to evaluate the results achieved in performing a single game assigned to the patient. Essentially, they allow identifying potential anomalies pertaining the game execution and, also, suggesting to the therapist changes in the game configuration for increasing the effectiveness of the game itself. In detail, they combine some precise information, i.e., the flags indicating the game has been started or completed (*Game.started* and *Game.completed*), with other vague ones, i.e., the motor gain (*MotorGain*), encoded as fuzzy variables assuming linguistic terms as values, ranging from very low to very high. Each of these linguistic terms has been modeled with fuzzy sets assuming trapezoid shapes. An as example of fuzzy variable, the motor gain (*MotorGain*), calculated as fuzzified value of the ratio between the measured ROMs (*ROM.interactionROMx* and *ROM.interactionROMy*), and their expected target values given by the therapists (*MotorGoal.targetROMx* and *MotorGoal.targetROMy*), is reported in Fig. 3.

Similarly, also cognitive gains are calculated as fuzzified values of the ratios between the number of moves or the amount of time employed to finish the game (Game.move and Game.time) and the maximum number of moves and amount of time given by the therapists to finish the game (GameConfiguration.

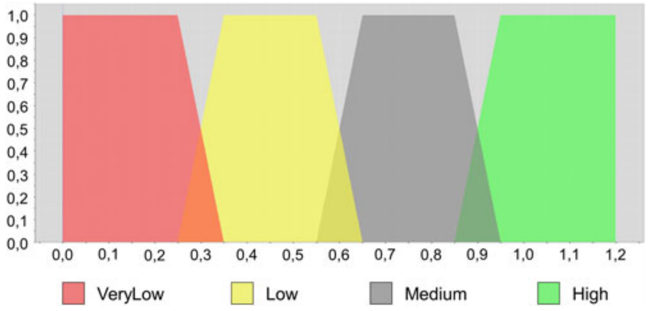

Fig. 3. MotorGain fuzzy variable and its terms defined on the basis of the ratio between the measured ROMs and their expected target values.

maxMoves and GameConfiguration.maxTime). A rule example operating at game level but on both precise and fuzzy information is the following:

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if
    $\mathbf{p} \in Patient$ AND
    $\mathbf{mg} \in MotorGoal$ AND $\mathbf{p}.goal = \mathbf{mg}$ AND
    $\mathbf{t} \in Treatment$ AND $\mathbf{p}.treatment = \mathbf{t}$ AND
    $\mathbf{s} \in Session$ AND $\mathbf{t}.session = \mathbf{s}$ AND
    $\mathbf{g} \in Game$ AND $\mathbf{s}.game = \mathbf{g}$ AND
    $\mathbf{g}.completed = true$ AND
    $MotorGainisVeryLow$
then
    $\mathbf{d} \in DSSResult$ AND $\mathbf{g}.decision = d$ AND
    $\mathbf{d}.type = game$ AND
    $\mathbf{d}.severity = red$ AND
    $\mathbf{d}.description =$“The motor gain in the $<\mathbf{mg}.exercise>$
    on $<\mathbf{mg}.discrict>$ is very low” AND
    $\mathbf{d}.suggestion =$ “The target ROM should be reduced since
    the patient was not able to operate with effective results”
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The second set of rules integrates different results regarding the motor functioning produced by all the games performed during the day and produces a summary, by taking into account the number of indications generated by each game and their severities, with the final aim of reducing the number of false positives and avoiding useless suggestions. For instance, if in the context of a single session made of more games, the patient has not produced the satisfying results from a motor perspective only in one of them, it is probably not a worrying condition since, in the remaining ones, the results are good and the exercises and the districts involved are the same for all the games. Thus, it is useless to alert the therapist with an indication characterized by a high severity, but it could be decreased to a lower grade.

Finally, the last set of rules integrates the summarized results regarding the motor functioning that are produced in consecutive sessions in order to determine if encouraging or poor improvements can be classified as occasional or relevant.

Both domain knowledge and hybrid production rules have been memorized into the DSS model repository.

IV. PILOT STUDY ON CLINICAL IMPACT

The effectiveness of the proposed solution was assessed by testing it with patients who had suffered from unilateral ischemic or hemorrhagic stroke, and were in the chronic phase, that is, at a distance of more than 6 months from the acute event. All the patients were monitored over a time interval of 6 weeks. The patients were divided into two groups: the first carried out a traditional, in-hospital rehabilitation program with a professional therapist; the second used the telerehabilitation solution at home, under the general supervision of a specialist. Both the groups performed the same number of rehabilitation sessions.

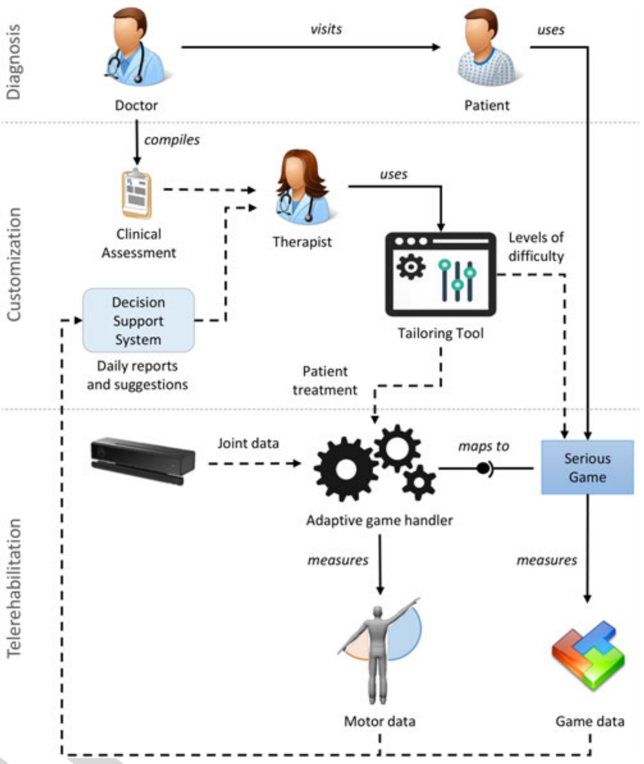


Fig. 4. Information flow within the pilot study.

Fig. 4 depicts the main actors, the activities, and the main components of the system involved in the telerehabilitation process, also showing the information flow. The patient’s level of impairments is evaluated by a doctor who performs the clinical assessment of the patient. As a result of such an assessment a report is produced, including information useful to the rehabilitation professionals to evaluate the patient’s ability, needs, preferences, and expectations. Next, the therapist uses the information contained in the clinical assessment report to tailor the telerehabilitation treatment by means of the tailoring tool. In more detail, given the motor deficiencies of the specific patient, the therapist defines, for each motor district of interest, the ROM in which the patient should exercise during the game sessions. Contextually, she/he modulates the level of difficulty of the serious games in order to trigger the individual’s motivational force toward the achievement of the intended outcome.

When the patient has started an exercise by playing a serious game, her/his movements are collected by the motion-tracking sensor and become the input for the adaptive game handler, which maps them with the game input dimensions. For instance, the patient’s right arm abduction in the game is mapped to the vertical movements of the pointer, while the left arm abduction to the horizontal ones. During the exercise, the session handler stores all the measures regarding movements, game score, and

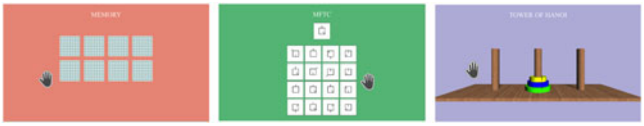


Fig. 5. Three serious games designed for the pilot study.

Fig. 6. Upper and lower limb neuromotor exercises.

execution time. The collected data are then used by the DSS to populate the daily digest and to produce inferences on the patient's rehabilitation process. Every day, the digests and the suggestions are given to the therapist, who can modify the telerehabilitation program for each specific patient. The modified program is then proposed to the patient in the next rehabilitation session.

Three well-known serious games were designed and implemented by using the unity development platform (see Fig. 5), namely memory, multiple features targets cancellation, Hanoi towers. Although the motion tracking component is able to track all the upper and lower limb neuromotorial exercises, in the study only the upper limb movements were considered (see Fig. 6).

A. Participants

Twenty subjects were recruited for the final protocol approved by the ethical committee. They received an informative brochure, with the system and the protocol described by trained personnel. The subjects who agreed to participate in the study were further examined and randomly assigned to a group (the control or telerehabilitation group). Informed consents were read and signed. Of the 20 participants recruited, 16 continued until the end of the trial, while 4 of them, 2 from each group, dropped out for reasons not linked to the experimentation.

The participants were enrolled through the ANON. The inclusion and exclusion criteria were defined as follows.

Inclusion criteria includes the following:

1) age $\geq$ 18 years;
2) diagnosis of unilateral ischemic or hemorrhagic stroke diagnosis, proven by computed tomography or magnetic resonance imaging;
3) stroke in chronic phase: distance from acute event more than 6 months;
4) score between 2 and 6 in the Chedoke McMaster-rating scale [30] for the corresponding upper limb section;
5) running time of the Nine Hole Peg Test (NHPT) $> 25/2$;
6) ability to move at least one peg in 180 s during NHPT.

Exclusion criteria includes the following:

1) cognitive impairment or behavioral dysfunction that does not allow an understanding of the planned activities and the participation in the trial;
2) presence of comorbidities that could affect the overall functioning of the subject;
3) refusal to sign the informed consent.

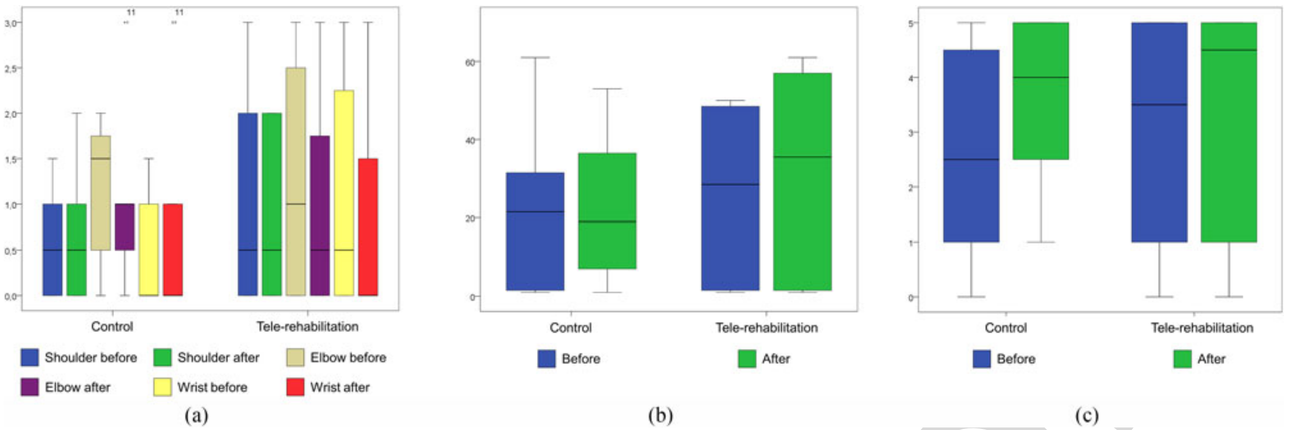
B. Results and Interpretation

A set of experiments was conducted employing a mixed-design analysis of variance in which the between-subject factor was the group (control or telerehabilitation). The rehabilitation performance was measured in terms of upper limb rehabilitation, upper extremity proximal motor control and dexterity, sensorimotor impairment, and spasticity. Cognitive measures (e.g., MMSE or MoCa) were not considered in the study since the time interval was not adequate to highlight a cognitive gain. The system makes use of cognitive serious games to perform neuromotor rehabilitation because they can increase the user engagement in the rehabilitation treatment, somewhat hiding the repetitive nature of a motor rehabilitation treatment. In more detail, the performance was measured, before and after the treatment, by using four metrics: the modified ashworth scale (MAS), considering the shoulders, elbows and wrists; the box and block test scale (BBT), considering the plegic side only; the Frenchay arm test (FAT); and, Fugl–Meyer assessment (FMA) [31], as modified by Lidmark and Harmin in[32]. In particular, the FMA assessment has already been proven to be reliable for the chronic stroke population [33], [34].

Our hypothesis was that there would not be a significant difference compared to the results obtained with a traditional rehabilitation approach, mainly because the telerehabilitation system is able to motivate the patient and provide feedback and suggestions to the therapist through the decision support service. In fact, by suggesting adjustments to the proposed therapy in terms of the level of difficulty and ROM, the system actively supports the therapist in tailoring the program to the specific patient, counterbalancing the lack of direct control of the patient.

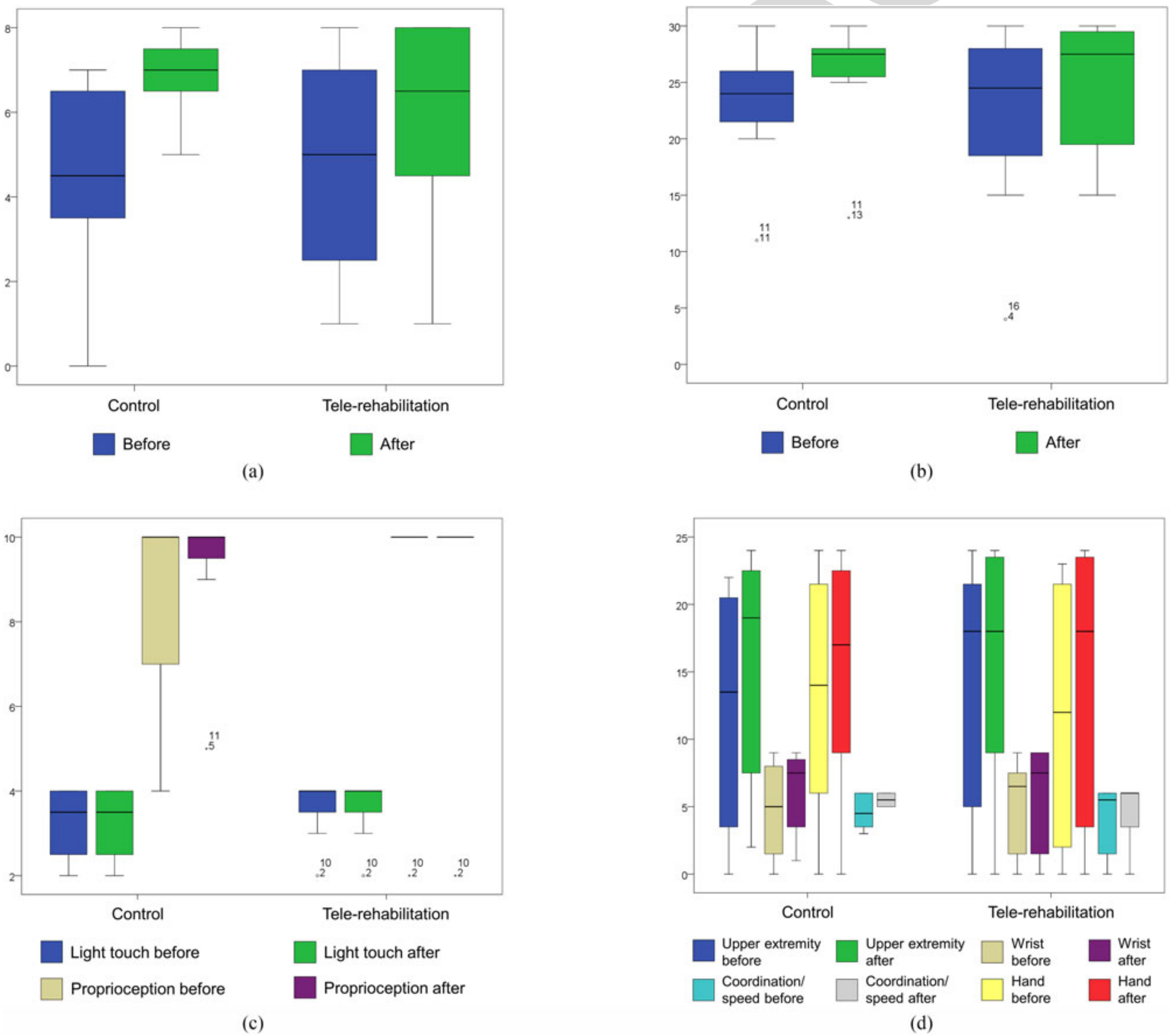
The results (see Figs. 7 and 8) indicate that the between-groups variable of group (control versus telerehabilitation) was not statistically significant in all the four considered scales. The analysis revealed a significant effect of the factor rehabilitation (before versus after) across the subjects on the FAT scale and on the FMA scale in terms of joint pain, passive joint range of motion and on motor function, both considering the upper extremities, wrists and hands, and coordination/speed. The analysis did not reveal, instead, a significant effect of rehabilitation on the MAS scale, on the BBT scale, and on the FMA scale concerning sensation (light touch and proprioception).

In more detail, with reference to the MAS scale, the analysis did not reveal a significant main effect of the between-groups variable of group both on shoulders, elbows, and wrists. A two-way interaction involving group and rehabilitation was not significant either. These findings suggest that the rehabilitation results achieved are not statistically dependent on the type of treatment (traditional versus telerehabilitation). Similar results were found for both the BBT scale and the FMA scale, consid-



(a) (b) (c)

Fig. 7. Box plot graphs. (a) MAS scores. (b) BBT scores. (c) FAT scores.



(a) (b)

(c) (d)

Fig. 8. Box plot graphs of FMA scores. (a) Joint pain. (b) Passive joint range of motion. (c) Sensation. (d) Motor function.

ering joint pain, passive joint ROM, sensation (light touch and proprioception), and motor function (upper extremities, wrists, hands, and coordination/speed). Specifically for the FAT scale, the analysis revealed a significant two-way interaction between rehabilitation and group ($F_{1,14} = 5.727,\ p < .05$). Observing the estimated marginal means, the FAT score shows a significant difference between the two groups, achieving a better performance with the traditional rehabilitation procedure.

The small sample size (16 subjects) of this pilot study limits the generalizability of the findings. A larger pilot study is necessary to assess the efficacy of the proposed adaptive, DSS-based home intervention in improving motor function in poststroke patients. Nonetheless, the experimental results are promising. Telerehabilitation achieved similar results, compared to the traditional intervention, in all the considered metrics. In the analysis, when a significant effect of the rehabilitation was found, particularly in the FMA scale in terms of joint pain, passive joint ROM, and motor function, the analysis did not reveal any significant difference between the rehabilitation methods.

When considering the FAT scale, the rehabilitation produced a significant effect but with a difference between the two considered interventions. In more detail, considerable improvements were achieved in both the control and the telerehabilitation groups , but they were more relevant when the traditional methods were used. To explain this specific result, it should be mentioned that the control group was characterized by a lower distance from the acute event compared with the telerehabilitation group. Since the control group exhibited a higher impairment on all the indicators, a more relevant improvement was expected. This consideration can be extended to all the metrics considered in the pilot study: given the composition of the two groups, the expectation of improvement was generally higher for the control group.

V. USER EXPERIENCE

In order to evaluate the user experience, a questionnaire based on the technology acceptance model (TAM) [35], extended to explore also enjoyment [36], aesthetics [37], control [38], and trust [39], was used. The TAM+ questionnaire so consisted of 34 items, which were divided into 8 domains: enjoyment, aesthetics, control, trust in technology, perceived usefulness, ease of use, intention to use, attitude. Cronbach's alpha index was used to assess the reliability of the psychometric measurement scales [40], calculated for each domain, a score ≥ 0.70 indicating reliability.

As a first step, the reliability of the measurement scale was investigated using the Cronbach's alpha. The results are summarized in Table I and show the reliability of each domain.

The TAM+ results (see Fig. 9) are clearly shifted toward the positive side (above the line indicating a neutral score). Six items out of eight showed a mean score of 6 or more (the highest item was the one concerning a positive attitude toward the system, including the willingness to use it or recommend it to others). The pattern of scores among different items is quite homogeneous, and also the low variability supports a generally positive attitude of the participants, which can be classified as definitely positive.

TABLE I
CRONBACH'S ALPHA OF THE CONSIDERED DOMAINS

Domain	Cronbach's alpha
Enjoyment	0.87
Aesthetics	0.91
Control	0.89
Trust in Technology	0.70
Perceived Usefulness	0.90
Intention to Use	0.89
Easy of Use	0.78
Attitude	0.92

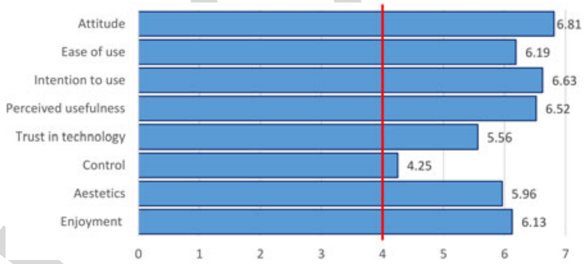


Fig. 9. User experience scores.

The item that scored a lower impact with the users was Control, although still above the neutral line. The analysis of variance showed a statistically significant difference between control and all the other domains ($F_{7,49} = 10.078, p < .002$), revealing that, with respect to the other features of the system, the participants had the perception of not completely managing the flow of the exercises and the use of the interface. This was probably due to the lack of any possibility to skip or repeat specific exercises, and to the requirement to finish the entire rehabilitation program established. Furthermore, the analysis showed a difference between trust in technology and attitude ($p < .03$, Bonferroni corrected). This finding highlights the importance of such a telerehabilitation technology, but, at the same time, this attitude is counterbalanced by a lesser confidence in privacy and security issues.

VI. CONCLUSION

This paper presented a novel solution for the telerehabilitation of poststroke patients. It uses serious games, motion-tracking technology, and a knowledge-based decision support service to provide patients, on the one hand, with an entertaining environment for treatment, on the other, with a complete solution for the tailoring of the rehabilitation exercises to meet the needs of the specific patients.

The innovation potential of the proposed solution can be described at different levels, which are as follows:

1) at the technological level: the novelty of the integration of a low cost motion sensor combined with customizable serious games, totally decoupled from the system, and with a decision support service, in the rehabilitation sector;

2) at the rehabilitation therapy level: a more effective, motivating, rewarding, and monitored therapy that is tailored to patients, together with a decision support service for therapists to personalize the rehabilitation exercises in accordance with the response of the patient;
3) at the socio-economic level: a better quality of life for impaired patients and their families, and a decrease in the social costs of rehabilitation practices; and a better exploitation of the skills and time of the therapists, who are automatically supported in the patient monitoring, thus, implying an increased number of patients that they are able to assist remotely.

The results of a pilot study on the clinical impact are promising. The telerehabilitation achieved similar results when compared to the traditional intervention, by considering four metrics widely used within the rehabilitation community. Moreover, a user study carried out with the patients enrolled in the pilot study showed a general acceptance of the proposed technology.

From a clinical perspective, our future work will focus on carrying out a larger pilot study, in which first, both cognitive and motor progress can be monitored over a longer time interval; second, the adjustments to the original plan made by a therapist can be compared and assessed with respect to those suggested by the decision support service; and lastly, the motivation and engagement of the patients using the system can be estimated and compared with those achieved by adopting traditional methods. Moreover, from an IT perspective, the migration of the proposed solution toward a hybrid cloud model will be evaluated in order to have the security and access of onpremises data centers and, contextually, benefit from the flexibility, reduced costs, and scalability of public clouds.

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Serious Games and In-Cloud Data Analytics for the Virtualization and Personalization of Rehabilitation Treatments

Giuseppe Caggianese, Salvatore Cuomo, Massimo Esposito, Marco Franceschini, Luigi Gallo,
Francesco Infarinato, Aniello Minutolo, Francesco Piccialli, and Paola Romano

***Abstract*—During the last years, the significant increase in the number of patients in need of rehabilitation has generated an unsustainable economic impact on healthcare systems, implying a reduction in therapeutic supervision and support for each patient. To address this problem, this paper proposes a telerehabilitation system based on serious games and in-cloud data analytics services, in accordance with Industry 4.0 design principles regarding modularity, service orientation, decentralization, virtualization, and real-time capability. The system, specialized for poststroke patients, comprises components for real-time acquisition of patient's motor data and a decision support service for their analysis. Raw data, reports, and recommendations are made available on the cloud to clinical operators to remotely assess rehabilitation outcomes and dynamically improve therapies. Furthermore, the results of a pilot study on the clinical impact deriving from the adoption of the proposed solution, and of a qualitative analysis about its acceptance, are presented and discussed.**

***Index Terms*—Data analytics, decision support systems (DSS), neuromotor rehabilitation, serious games, telerehabilitation.**

I. Introduction

THE significant increase in the number of patients in need of rehabilitation has generated an unsustainable economic impact on healthcare systems, implying a reduction in the amount of therapeutic supervision and support for each patient. This is particularly true for poststroke patients [1]. Stroke afflicts about two million people every year in Europe and is the leading cause of serious, long-term adult disability worldwide [2]. It affects brain activity leading to deficits in motor and cognitive functions, at least for a certain time, thus, negatively impacting on the patient's ability to perform daily activities. Inpatient rehabilitation programs guided by therapists are the primary means to address and improve impaired motor and cognitive functioning caused by a stroke [3]. However, poststroke patients do not completely recover their original functional level for different reasons, e.g., stroke severity, lack of motivation to perform rehabilitative exercises, or insufficient, and/or nonoptimal training in the initial weeks following the stroke. Unfortunately, only a limited number of individuals with residual deficits in functioning receive outpatient rehabilitation due to inadequate health service funding [4]. This is extremely disappointing since, in the opinion of many therapists, the number of inpatient rehabilitation exercises is generally insufficient and the lack of regularity of outpatient rehabilitation exercises prevents improvements from being completely effective [5].

In the last few years, telerehabilitation systems have been proposed as a very promising solution to support and motivate poststroke patients in the performance of rehabilitation exercises at their own home, with only limited, or even without, human supervision. In addition, systematic reviews and clinical trial data have shown that serious games can be used to improve motor rehabilitation in poststroke patients for a range of functional deficits [6], while increasing patient engagement [7]. Nonetheless, some factors currently limit the adoption of game-based stroke rehabilitation in real scenarios [8], [9], including the following:

1) expensiveness, invasiveness, and nonportability into the home setting;
2) impossibility of customizing the therapy for the specific patient;
3) excessive complexity and therefore unsuitability to be used by nontechnical therapists and lack of attractiveness for the patients;
4) lack of automatic, adaptive methods in requesting prompt intervention of therapists, in order to limit frustration and abandonment and increase motivation and engagement.

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This paper proposes, as main contribution, a poststroke telerehabilitation system based on serious games and in-cloud data analytics services. The system exhibits its novelty in the way that it provides an extensive set of features addressing all the above mentioned limitations and devised in accordance with some of the design principles, namely, modularity, service orientation, decentralization, virtualization, and real-time capability, identified in [10] with reference to the Industry 4.0, and still valid for the health scenario here considered. In detail, the proposed system integrates a set of neuromotor and neurocognitive serious games, based on low-cost and uncumbersome sensing devices, able to adapt to different stroke-related functional impairments (modularity), in order to collect data and enhance the patient's engagement. Moreover, it integrates decision support facilities, arranged as cloud services that can be delivered and reached anywhere, anyhow and at any time (service orientation), able to approximate medical expertise and human-like reasoning capabilities, in order to remotely analyze the collected data and support therapists in refining patients' daily exercises (decentralization). The whole system is able to operate in near real time (real-time capability), allowing for delivery of a patient-centric model of care, where therapists are not obliged to be physically present at the patient's home, but they are automatically aided in providing personalized indications or feedbacks about patient's therapy exercises in a virtualized manner (virtualization).

II. RELATED WORK

In this section, different rehabilitation systems and frameworks have been analyzed and compared to the proposed system according to a set of requirements, which were identified by the doctors and therapists involved in the pilot study as needed for use in real scenarios:

1) customizable therapy;
2) patient engagement;
3) expensiveness, invasiveness and nonportability;
4) reduced human supervision;
5) automated exercise monitoring and analysis;
6) extendibility of the serious game environment.

For each requirement, the original contribution of the proposed system has been described by highlighting the main differences with the other approaches.

The first requirement is the capability of offering a functionality for the customizing of the therapy for specific patients and specific rehabilitation targets. While the works [11]–[13] completely support this requirement for therapy customization, others, namely [14]–[19], [19]–[24] offer only limited and partial mechanisms to tailor the exercises for individual patients. In this respect, the proposed system provides the therapists, with little to no programming skills, with a user-friendly interface that allows the definition of exercises tailored to the needs of specific patients.

Second, the therapists emphasized the need to enhance the patients' engagement through gaming. In fact, scientific evidence suggests that when a patient focuses on the game rather than her/his impairment, the exercise becomes more enjoyable and is more likely to be maintained over the many sessions needed to induce a gain in motor functioning [25]. This aspect proves to be almost totally supported in all the works examined. The proposed system, in addition to enhancing the patient's engagement through gaming, further involves the patients by focusing on rewarding cognitive exercises while simultaneously enhancing motor functions. This choice is justified by the fact that studies in literature have shown that presenting the patient with a motivating and distracting cognitive challenge can facilitate the engagement with the serious game [26], by reducing the possibility of any abandonment of the therapy due to depression and frustration generated by the stroke trauma and the extended period of recovery.

The need of space and cost minimization was also highlighted and considered worthy of analysis. Some of the works are based on uncumbersome and low cost devices that can be easily used in home settings [22]–[24], whereas all the others require more complex set-ups. In this respect, the proposed system is based on low cost and on the shelf devices easily transportable and installable into the home, providing an expedient and practical mode of ongoing care.

Furthermore, the therapists requested the possibility for the patient to perform the rehabilitation program independently, so requiring a less direct involvement from the medical staff. While the works [12], [13], [15]–[17], [20], [22], [24] respect this requirement, others, namely, [11], [18], [21], offer only a limited set of functionalities to minimize the involvement of the therapist in patient's daily rehabilitation. The proposed solution offers to the patient the possibility of performing, on a regular basis, rehabilitation programs independently and quietly at home in a family context, without the need for the continuous presence of therapists. Indeed, the amount of feedback given by the system on the execution of the rehabilitation exercises allows for less direct involvement from the therapists and a greater awareness on the part of the patient.

Another important requirement highlighted by the therapists is the capability of an automatic monitoring of the exercises assigned to the patients in order to, on the one hand, draw up and complete a daily report about the state of the therapy and, on the other, to automatically analyze and correlate the collected results. In this respect, while some works [11], [12], [20] offer both a monitoring and automatic analysis of patient progress and performance, some others [13], [19], [21]–[23], instead, provide only the monitoring functionality. The works [16], [17] are mainly focused on the evaluation of patient performance only. Compared to relevant literature, the proposed system is able to automatically monitor the patient's exercises, also providing the therapist with a complete and detailed daily report, so improving knowledge on the patient's rehabilitation progress. In more detail, it is able to analyze and correlate the results of each daily exercise session, quantitatively and qualitatively reason on them by encoding medical expertise and, finally, notifying the therapists about any encouraging or poor motor, cognitive or psychological improvements obtained by the patients. Depending on these outcomes, it can suggest to the therapists some adjustments to the daily therapy program for the patients in order to avoid their frustration and abandonment, in the case of

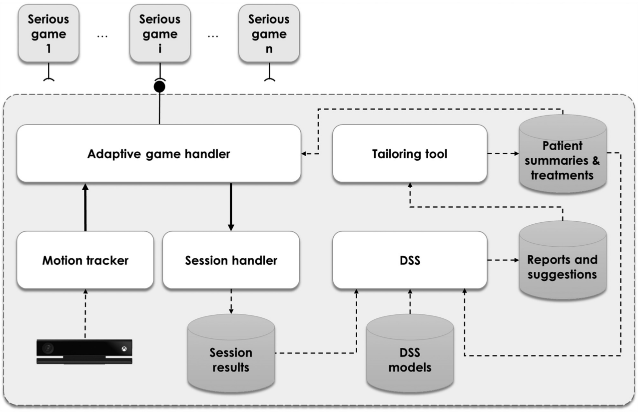

Fig. 1. High-level system architecture.

poor results, or to reinforce their engagement and awareness, in the case of encouraging improvements.

Finally, a further requirement arises with respect to the need to support an easy extension of available serious games, in order to make the device itself a more appealing solution for therapists and patients. However, none of the considered works provides seamless integration mechanisms to access the suite of serious games on offer while, in the proposed solution, new serious games can be easily added to the suite if they are developed in a manner consistent with the interface proposed by the system.

III. SMART TELEREHABILITATION SYSTEM

A. System Architecture

As shown in Fig. 1, the system is organized in different components. Due to real-time constraints, the components interacting with depth sensors, namely, the *adaptive game handler*, the *motion tracker* and the *session handler*, and all the *serious games*, are deployed locally. The other components, namely, the *tailoring tool* and the *Decision support system (DSS)*, are available as web services hosted on a private cloud to be accessed remotely by therapists and medical experts. The choice of a private cloud is due to the need of keeping a direct control over where sensitive data resides and who can access them. Thus, all the data are safely memorized in storage repositories of the private cloud, enabling efficient retrieval, updates and quick transfers as and when required, in accordance with the proper authorization rights.

Each *serious game* exposes a common interface, which includes, as input, *level of difficulty*, *pointing* and *selection* features and, as output, *total score* and *execution time*.

The *adaptive game handler* is in charge of decoupling the serious games from the *motion tracker*, which tracks the patient's movements by using the Microsoft Kinect v2 sensor. It can map from one to three user movements to the serious game logic, by connecting the received tracking data to the serious game pointing and selection actions. Thanks to this component, new serious games can be easily connected to the system if they conform to the common interface. All the session data produced by both the motion tracker and the serious games will be sent and handled by the *session handler*, which is in charge of storing them into the *session results* repository.

The *tailoring tool* is the primary point of access for the therapist, where she/he can specify the patient summary and the rehabilitation goals. These latter are expressed as a list of objectives for each motor district, characterized by the anatomical problem of interest (e.g., left shoulder abduction or right leg flexion), the initial range of motion (ROM) the subject is able to perform, and the target ROM the therapist desires to reach. All this information is stored in the *patient summaries and treatments* repository. Moreover, this component is used by the therapist to visualize the daily report of the patient's activities and the suggestions for improvements in the customization of the therapy. This information is automatically generated by the *DSS*, by employing knowledge-based models contained in a local store named the *DSS model*, and successively memorized in the *report and suggestions* repository.

The tailoring tool and the DSS are developed and deployed as three-tier Software as a Service web applications that make use of Apache at the web server tier, Tomcat at the application tier with MySQL as the database server. They are both wrapped into a set of service components according to the web service resource framework standards and deployed on a private Infrastructure as a Service cloud built by using OpenNebula.

Further details on the adaptive game handler and on the DSS are provided in the following sections.

B. Adaptive Game Handler

The adaptive game handler accesses the patient treatment as recorded by the therapist. Such an initial configuration should contain, for each serious game included in the patient therapy, the following information:

1) at least one but no more than two physical exercises to perform (abductions, extensions, etc.) with the indication of the involved motor district to track;
2) for each motor district, the ROM in which the patient should exercise;
3) for each serious game, the selection technique (wait-to-click, with an indication of the trigger time, or grabbing);
4) for each serious game, its level of difficulty.

By using such configuration data, the component can filter the patient's joint data provided by the motion tracker, computing the angles only on those motor districts selected by the therapist.

Pointing can be performed by using either two items of input data (e.g., (x, y)) or a single one (e.g., p, defining the position of the pointer in a fixed path that covers all the game objects). All the pointing data are normalized in $[0, 1]$ by using the ROM configuration set by the therapist. They are further smoothed by means of a velocity-based filter [27]. Motion data outside the active interval are pruned before being sent to the serious game. However, they will be sent to the session handler to enable further analyses. For the selection task, two different interaction techniques can be used: *wait-to-click*, in which the patient has to maintain the pointer over the selected object for an amount of time, defined by the therapist, to confirm the selection; and *grabbing*, which requires the patient to close her/his hand in a fist to confirm the selection. The selection values are 0 or 1.

Relevant data are sent to the session handler. Such data include the following:

1) the maximum axis-angles performed by the patient in the assigned exercises;
2) the minimum axis-angles performed by the patient in the assigned exercises;
3) the game score;
4) the execution time.

C. Decision Support Service

This service is in charge of automatically integrating, analyzing, and correlating, for each patient, the results of each daily exercise session with information pertaining her/his profile and treatment plan, reasoning on them by approximating medical expertise and human-like reasoning capabilities, and finally, generating a complete and rich daily report, where motor improvements are highlighted and some possible adjustments to the daily patients' treatment are suggested.

From a more technical perspective, the DSS essentially relies on hybrid production rules built on the top of ontological and fuzzy primitives and on the inference engine proposed in [28] to reason on them in order to obtain transparent, qualitative and interpretable insights, and suggestions. Each rule is expressed in the form "*if premises then decision option,*" where a single *condition* corresponds to a datum collected during the patient's exercise or extracted from her/his summary or treatment plan, whereas a *decision option* is an indication about hopeful or unsatisfactory treatment results or a suggestion about some possible treatment adjustments.

In detail, on the one hand, ontologies have been used to represent both the information handled by the telerehabilitation system and the medical knowledge possessed by the professionals involved in the rehabilitation process. This whole set of information and knowledge has been elicited and modeled, with the cooperation of engineers, doctors, and therapists, in terms of concepts, properties, and relationships by exploiting a shared vocabulary, so as to grant fundamental characteristics of being formal, semantically well-defined and interpretable. All this domain knowledge has been coded in the form <*subject, predicate, object*>, according to the *N*-triples syntax [29]. The main concepts of the ontology are shown in Fig. 2.

Fuzzy logic, on the other hand, has been adopted to model qualitative knowledge in the form of fuzzy variables assuming, as values, linguistic terms, such as low, medium, and high. These linguistic terms have been elicited and modeled, also in this case with the cooperation of engineers, doctors, and therapists, in the form of smooth sets of values, with a membership degree defined in a continuous range of truthvalues between 0 and 1. Such a way, medical knowledge owned by doctors and therapists has been represented more realistically, since it abounds of graded and qualitative formulations in place of precise thresholds representing oversimplifications of the reality. All the hybrid production rules have been encoded by using ontological concepts and properties to express quantitative information as well as fuzzy variables and linguistic terms to represent qualitative information. In particular, three different sets of hybrid production rules have been arranged, which take into account data produced by the single game, collected daily within a session or collected during different consecutive sessions.

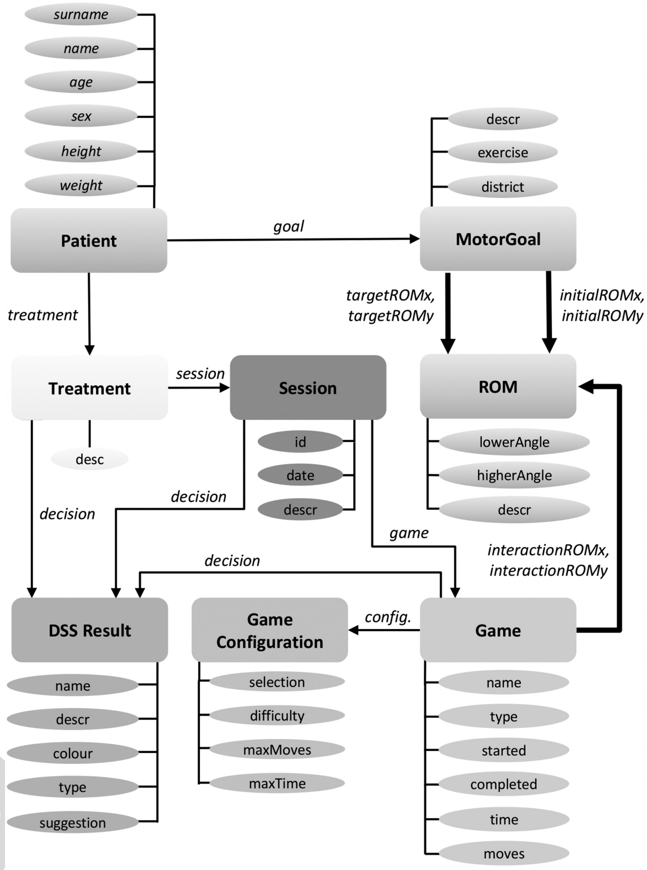

Fig. 2. Ontology model for describing the domain of interest.

The first set of rules operates at game level in order to evaluate the results achieved in performing a single game assigned to the patient. Essentially, they allow identifying potential anomalies pertaining the game execution and, also, suggesting to the therapist changes in the game configuration for increasing the effectiveness of the game itself. In detail, they combine some precise information, i.e., the flags indicating the game has been started or completed (*Game.started* and *Game.completed*), with other vague ones, i.e., the motor gain (*MotorGain*), encoded as fuzzy variables assuming linguistic terms as values, ranging from very low to very high. Each of these linguistic terms has been modeled with fuzzy sets assuming trapezoid shapes. An as example of fuzzy variable, the motor gain (*MotorGain*), calculated as fuzzified value of the ratio between the measured ROMs (*ROM.interactionROMx* and *ROM.interactionROMy*), and their expected target values given by the therapists (*MotorGoal.targetROMx* and *MotorGoal.targetROMy*), is reported in Fig. 3.

Similarly, also cognitive gains are calculated as fuzzified values of the ratios between the number of moves or the amount of time employed to finish the game (Game.move and Game.time) and the maximum number of moves and amount of time given by the therapists to finish the game (GameConfiguration.

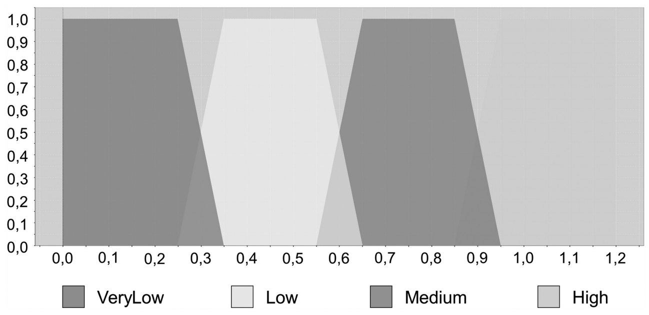

Fig. 3. MotorGain fuzzy variable and its terms defined on the basis of the ratio between the measured ROMs and their expected target values.

maxMoves and GameConfiguration.maxTime). A rule example operating at game level but on both precise and fuzzy information is the following:

```
if
    $\mathbf{p} \in Patient$ AND
    $\mathbf{mg} \in MotorGoal$ AND $\mathbf{p}.goal = \mathbf{mg}$ AND
    $\mathbf{t} \in Treatment$ AND $\mathbf{p}.treatment = \mathbf{t}$ AND
    $\mathbf{s} \in Session$ AND $\mathbf{t}.session = \mathbf{s}$ AND
    $\mathbf{g} \in Game$ AND $\mathbf{s}.game = \mathbf{g}$ AND
    $\mathbf{g}.completed = true$ AND
    $MotorGainisVeryLow$
then
    $\mathbf{d} \in DSSResult$ AND $\mathbf{g}.decision = d$ AND
    $\mathbf{d}.type = game$ AND
    $\mathbf{d}.severity = red$ AND
    $\mathbf{d}.description =$ "The motor gain in the $<\mathbf{mg}.exercise>$
    on $<\mathbf{mg}.discrict>$ is very low" AND
    $\mathbf{d}.suggestion =$ "The target ROM should be reduced since
    the patient was not able to operate with effective results"
```

The second set of rules integrates different results regarding the motor functioning produced by all the games performed during the day and produces a summary, by taking into account the number of indications generated by each game and their severities, with the final aim of reducing the number of false positives and avoiding useless suggestions. For instance, if in the context of a single session made of more games, the patient has not produced the satisfying results from a motor perspective only in one of them, it is probably not a worrying condition since, in the remaining ones, the results are good and the exercises and the districts involved are the same for all the games. Thus, it is useless to alert the therapist with an indication characterized by a high severity, but it could be decreased to a lower grade.

Finally, the last set of rules integrates the summarized results regarding the motor functioning that are produced in consecutive sessions in order to determine if encouraging or poor improvements can be classified as occasional or relevant.

Both domain knowledge and hybrid production rules have been memorized into the DSS model repository.

IV. PILOT STUDY ON CLINICAL IMPACT

The effectiveness of the proposed solution was assessed by testing it with patients who had suffered from unilateral ischemic or hemorrhagic stroke, and were in the chronic phase, that is, at a distance of more than 6 months from the acute event. All the patients were monitored over a time interval of 6 weeks. The patients were divided into two groups: the first carried out a traditional, in-hospital rehabilitation program with a professional therapist; the second used the telerehabilitation solution at home, under the general supervision of a specialist. Both the groups performed the same number of rehabilitation sessions.

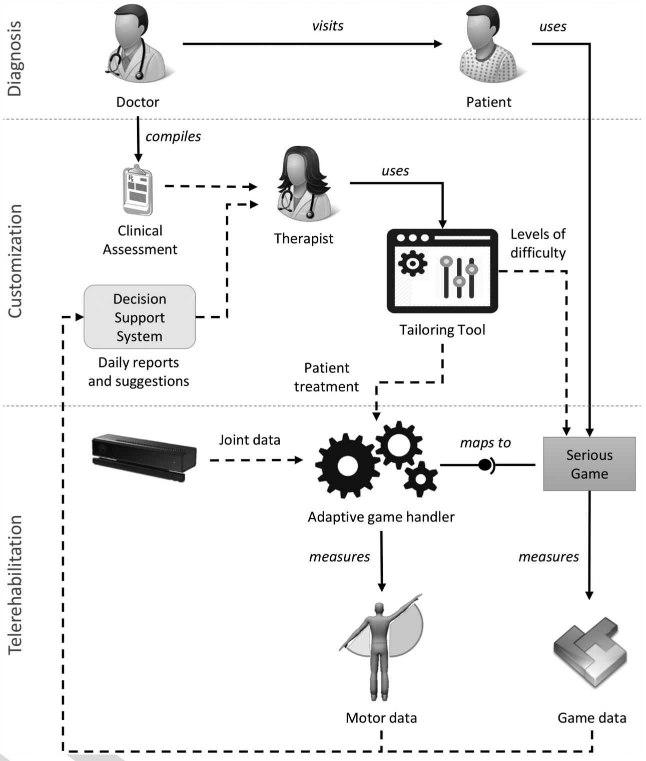

Fig. 4. Information flow within the pilot study.

Fig. 4 depicts the main actors, the activities, and the main components of the system involved in the telerehabilitation process, also showing the information flow. The patient's level of impairments is evaluated by a doctor who performs the clinical assessment of the patient. As a result of such an assessment a report is produced, including information useful to the rehabilitation professionals to evaluate the patient's ability, needs, preferences, and expectations. Next, the therapist uses the information contained in the clinical assessment report to tailor the telerehabilitation treatment by means of the tailoring tool. In more detail, given the motor deficiencies of the specific patient, the therapist defines, for each motor district of interest, the ROM in which the patient should exercise during the game sessions. Contextually, she/he modulates the level of difficulty of the serious games in order to trigger the individual's motivational force toward the achievement of the intended outcome.

When the patient has started an exercise by playing a serious game, her/his movements are collected by the motion-tracking sensor and become the input for the adaptive game handler, which maps them with the game input dimensions. For instance, the patient's right arm abduction in the game is mapped to the vertical movements of the pointer, while the left arm abduction to the horizontal ones. During the exercise, the session handler stores all the measures regarding movements, game score, and

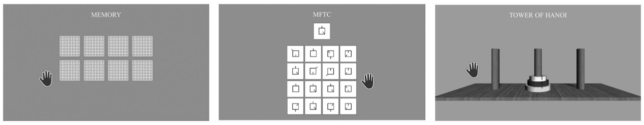

Fig. 5. Three serious games designed for the pilot study.

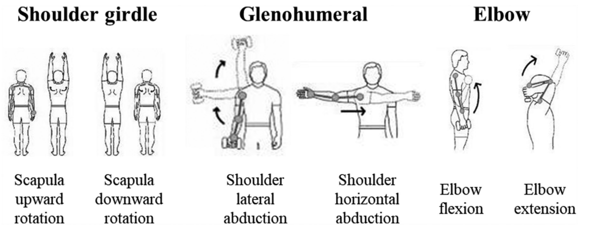

Fig. 6. Upper and lower limb neuromotor exercises.

execution time. The collected data are then used by the DSS to populate the daily digest and to produce inferences on the patient's rehabilitation process. Every day, the digests and the suggestions are given to the therapist, who can modify the telerehabilitation program for each specific patient. The modified program is then proposed to the patient in the next rehabilitation session.

Three well-known serious games were designed and implemented by using the unity development platform (see Fig. 5), namely memory, multiple features targets cancellation, Hanoi towers. Although the motion tracking component is able to track all the upper and lower limb neuromotorial exercises, in the study only the upper limb movements were considered (see Fig. 6).

A. Participants

Twenty subjects were recruited for the final protocol approved by the ethical committee. They received an informative brochure, with the system and the protocol described by trained personnel. The subjects who agreed to participate in the study were further examined and randomly assigned to a group (the control or telerehabilitation group). Informed consents were read and signed. Of the 20 participants recruited, 16 continued until the end of the trial, while 4 of them, 2 from each group, dropped out for reasons not linked to the experimentation.

The participants were enrolled through the ANON. The inclusion and exclusion criteria were defined as follows.

Inclusion criteria includes the following:

1) age ≥ 18 years;
2) diagnosis of unilateral ischemic or hemorrhagic stroke diagnosis, proven by computed tomography or magnetic resonance imaging;
3) stroke in chronic phase: distance from acute event more than 6 months;
4) score between 2 and 6 in the Chedoke McMaster-rating scale [30] for the corresponding upper limb section;
5) running time of the Nine Hole Peg Test (NHPT) $> 25/2$;
6) ability to move at least one peg in 180 s during NHPT.

Exclusion criteria includes the following:

1) cognitive impairment or behavioral dysfunction that does not allow an understanding of the planned activities and the participation in the trial;
2) presence of comorbidities that could affect the overall functioning of the subject;
3) refusal to sign the informed consent.

B. Results and Interpretation

A set of experiments was conducted employing a mixed-design analysis of variance in which the between-subject factor was the group (control or telerehabilitation). The rehabilitation performance was measured in terms of upper limb rehabilitation, upper extremity proximal motor control and dexterity, sensorimotor impairment, and spasticity. Cognitive measures (e.g., MMSE or MoCa) were not considered in the study since the time interval was not adequate to highlight a cognitive gain. The system makes use of cognitive serious games to perform neuromotor rehabilitation because they can increase the user engagement in the rehabilitation treatment, somewhat hiding the repetitive nature of a motor rehabilitation treatment. In more detail, the performance was measured, before and after the treatment, by using four metrics: the modified ashworth scale (MAS), considering the shoulders, elbows and wrists; the box and block test scale (BBT), considering the plegic side only; the Frenchay arm test (FAT); and, Fugl–Meyer assessment (FMA) [31], as modified by Lidmark and Harmin in[32]. In particular, the FMA assessment has already been proven to be reliable for the chronic stroke population [33], [34].

Our hypothesis was that there would not be a significant difference compared to the results obtained with a traditional rehabilitation approach, mainly because the telerehabilitation system is able to motivate the patient and provide feedback and suggestions to the therapist through the decision support service. In fact, by suggesting adjustments to the proposed therapy in terms of the level of difficulty and ROM, the system actively supports the therapist in tailoring the program to the specific patient, counterbalancing the lack of direct control of the patient.

The results (see Figs. 7 and 8) indicate that the between-groups variable of group (control versus telerehabilitation) was not statistically significant in all the four considered scales. The analysis revealed a significant effect of the factor rehabilitation (before versus after) across the subjects on the FAT scale and on the FMA scale in terms of joint pain, passive joint range of motion and on motor function, both considering the upper extremities, wrists and hands, and coordination/speed. The analysis did not reveal, instead, a significant effect of rehabilitation on the MAS scale, on the BBT scale, and on the FMA scale concerning sensation (light touch and proprioception).

In more detail, with reference to the MAS scale, the analysis did not reveal a significant main effect of the between-groups variable of group both on shoulders, elbows, and wrists. A two-way interaction involving group and rehabilitation was not significant either. These findings suggest that the rehabilitation results achieved are not statistically dependent on the type of treatment (traditional versus telerehabilitation). Similar results were found for both the BBT scale and the FMA scale, consid-

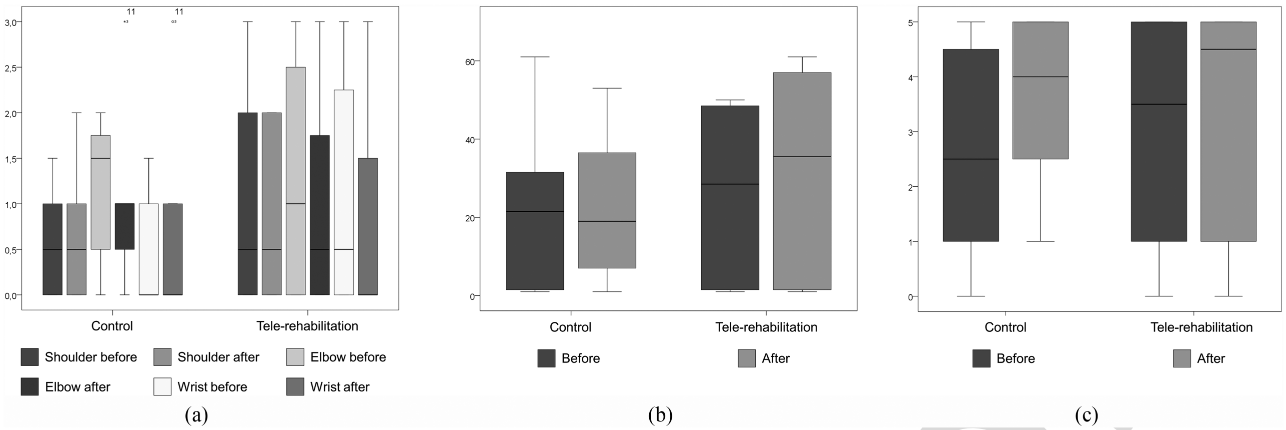

Fig. 7. Box plot graphs. (a) MAS scores. (b) BBT scores. (c) FAT scores.

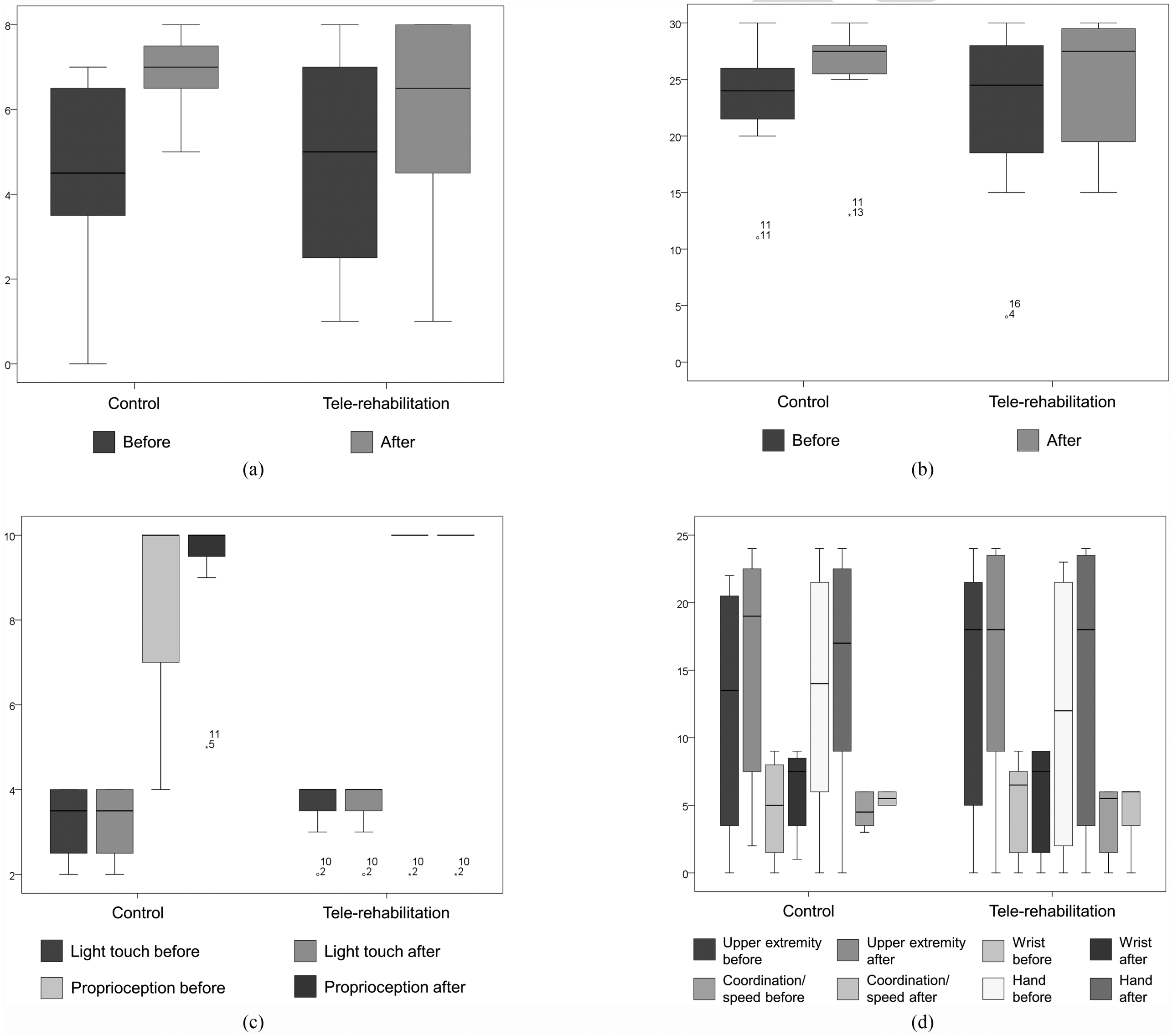

Fig. 8. Box plot graphs of FMA scores. (a) Joint pain. (b) Passive joint range of motion. (c) Sensation. (d) Motor function.

ering joint pain, passive joint ROM, sensation (light touch and proprioception), and motor function (upper extremities, wrists, hands, and coordination/speed). Specifically for the FAT scale, the analysis revealed a significant two-way interaction between rehabilitation and group ($F_{1,14} = 5.727,\ p < .05$). Observing the estimated marginal means, the FAT score shows a significant difference between the two groups, achieving a better performance with the traditional rehabilitation procedure.

The small sample size (16 subjects) of this pilot study limits the generalizability of the findings. A larger pilot study is necessary to assess the efficacy of the proposed adaptive, DSS-based home intervention in improving motor function in poststroke patients. Nonetheless, the experimental results are promising. Telerehabilitation achieved similar results, compared to the traditional intervention, in all the considered metrics. In the analysis, when a significant effect of the rehabilitation was found, particularly in the FMA scale in terms of joint pain, passive joint ROM, and motor function, the analysis did not reveal any significant difference between the rehabilitation methods.

When considering the FAT scale, the rehabilitation produced a significant effect but with a difference between the two considered interventions. In more detail, considerable improvements were achieved in both the control and the telerehabilitation groups , but they were more relevant when the traditional methods were used. To explain this specific result, it should be mentioned that the control group was characterized by a lower distance from the acute event compared with the telerehabilitation group. Since the control group exhibited a higher impairment on all the indicators, a more relevant improvement was expected. This consideration can be extended to all the metrics considered in the pilot study: given the composition of the two groups, the expectation of improvement was generally higher for the control group.

V. USER EXPERIENCE

In order to evaluate the user experience, a questionnaire based on the technology acceptance model (TAM) [35], extended to explore also enjoyment [36], aesthetics [37], control [38], and trust [39], was used. The TAM+ questionnaire so consisted of 34 items, which were divided into 8 domains: enjoyment, aesthetics, control, trust in technology, perceived usefulness, ease of use, intention to use, attitude. Cronbach's alpha index was used to assess the reliability of the psychometric measurement scales [40], calculated for each domain, a score ≥ 0.70 indicating reliability.

As a first step, the reliability of the measurement scale was investigated using the Cronbach's alpha. The results are summarized in Table I and show the reliability of each domain.

The TAM+ results (see Fig. 9) are clearly shifted toward the positive side (above the line indicating a neutral score). Six items out of eight showed a mean score of 6 or more (the highest item was the one concerning a positive attitude toward the system, including the willingness to use it or recommend it to others). The pattern of scores among different items is quite homogeneous, and also the low variability supports a generally positive attitude of the participants, which can be classified as definitely positive.

TABLE I
CRONBACH'S ALPHA OF THE CONSIDERED DOMAINS

Domain	Cronbach's alpha
Enjoyment	0.87
Aesthetics	0.91
Control	0.89
Trust in Technology	0.70
Perceived Usefulness	0.90
Intention to Use	0.89
Easy of Use	0.78
Attitude	0.92

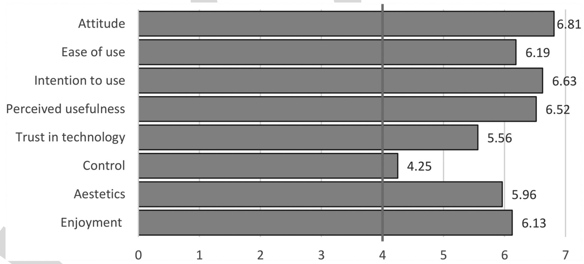

Fig. 9. User experience scores.

The item that scored a lower impact with the users was Control, although still above the neutral line. The analysis of variance showed a statistically significant difference between control and all the other domains ($F_{7,49} = 10.078, p < .002$), revealing that, with respect to the other features of the system, the participants had the perception of not completely managing the flow of the exercises and the use of the interface. This was probably due to the lack of any possibility to skip or repeat specific exercises, and to the requirement to finish the entire rehabilitation program established. Furthermore, the analysis showed a difference between trust in technology and attitude ($p < .03$, Bonferroni corrected). This finding highlights the importance of such a telerehabilitation technology, but, at the same time, this attitude is counterbalanced by a lesser confidence in privacy and security issues.

VI. CONCLUSION

This paper presented a novel solution for the telerehabilitation of poststroke patients. It uses serious games, motion-tracking technology, and a knowledge-based decision support service to provide patients, on the one hand, with an entertaining environment for treatment, on the other, with a complete solution for the tailoring of the rehabilitation exercises to meet the needs of the specific patients.

The innovation potential of the proposed solution can be described at different levels, which are as follows:

1) at the technological level: the novelty of the integration of a low cost motion sensor combined with customizable serious games, totally decoupled from the system, and with a decision support service, in the rehabilitation sector;

2) at the rehabilitation therapy level: a more effective, motivating, rewarding, and monitored therapy that is tailored to patients, together with a decision support service for therapists to personalize the rehabilitation exercises in accordance with the response of the patient;
3) at the socio-economic level: a better quality of life for impaired patients and their families, and a decrease in the social costs of rehabilitation practices; and a better exploitation of the skills and time of the therapists, who are automatically supported in the patient monitoring, thus, implying an increased number of patients that they are able to assist remotely.

The results of a pilot study on the clinical impact are promising. The telerehabilitation achieved similar results when compared to the traditional intervention, by considering four metrics widely used within the rehabilitation community. Moreover, a user study carried out with the patients enrolled in the pilot study showed a general acceptance of the proposed technology.

From a clinical perspective, our future work will focus on carrying out a larger pilot study, in which first, both cognitive and motor progress can be monitored over a longer time interval; second, the adjustments to the original plan made by a therapist can be compared and assessed with respect to those suggested by the decision support service; and lastly, the motivation and engagement of the patients using the system can be estimated and compared with those achieved by adopting traditional methods. Moreover, from an IT perspective, the migration of the proposed solution toward a hybrid cloud model will be evaluated in order to have the security and access of onpremises data centers and, contextually, benefit from the flexibility, reduced costs, and scalability of public clouds.

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