

A Modular Web-Based Framework for Inclusive Telerehabilitation and Faster Serious Game Development

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Abstract. Introduction: Adherence to telerehabilitation is frequently hindered by hardware obsolescence and the lack of diverse therapeutic content, leading to patient boredom and high dropout rates. **Objective:** This paper proposes a modular, web-based framework designed to decouple kinematic sensing from game logic, fostering a rapid-prototyping ecosystem for diverse serious games. **Methodology:** The architecture utilizes a "Virtual Sensor" layer that abstracts computer vision data (from MediaPipe/TensorFlow.js) into standardized therapeutic metrics ($[0, 1]$ scale), ensuring inclusive gameplay regardless of the patient's individual range of motion and processed entirely on the client side to ensure real-time feedback. **Results:** By enabling the quick development of varied, short-duration games, the framework aims to maintain high adherence levels and empowerment among elderly patients, as reported in clinical exergaming studies, while also facilitating a "zero-install" environment that lowers the barrier to entry for elderly patients and independent game developers.

Keywords telerehabilitation; serious games; computer vision; modular architecture; calibration.

1. Introduction

The global healthcare system is currently facing a dual challenge: a rapidly aging population and a significant increase in chronic conditions requiring long-term motor rehabilitation. Stroke remains a leading cause of long-term disability, with over 12 million new cases reported annually [World Stroke Organization 2024], frequently resulting in motor impairments that reduce the quality of life for up to 85% of survivors [He et al. 2024]. This reality creates a demand for physical therapy that traditional, in-clinic models struggle to meet due to high costs and geographical barriers.

Telerehabilitation, delivered through information and communication technologies, has emerged as a decentralized alternative that maintains clinical outcomes while fostering patient autonomy. In this context, Serious Games focused on exercise (exergames) play a crucial role by using gamification to increase adherence and motivation. However, the scientific and commercial progress of these games is currently hindered by strong coupling to the original hardware.

While exergaming is a promising alternative to traditional exercise-promoting empowerment and psychosocial well-being among older adults-its clinical success is often limited by poor adherence [Verheijden Klompstra et al. 2014]. Mastery and enjoyment are critical factors for sustained use; therefore, a system that allows for a

variety of engaging experiences is essential to prevent dropout in home-based settings [Rüth et al. 2023].

For over a decade, clinically validated systems such as *VirtuAlter* [de Medeiros 2018], *VirtualPT* [Heiyanthuduwa et al. 2020] and *MERLIN* [Rozevink et al. 2021], were built upon specialized hardware. With the price or discontinuation of such hardware, these software solutions became inaccessible for home-based users. While modern deep learning-based Human Pose Estimation (HPE) and web frameworks allows for motion tracking using standard RGB webcams, most existing exergames remain with low modularity and dependance on installation on personal computers.

To democratize access to digital health, we propose a modular, web-based framework that decouples kinematic sensing from serious game logic. By transforming commodity webcams or smartphones into "Virtual Sensors" using edge-native computer vision, our framework ensures that therapy is hardware-agnostic. This paper presents an architecture that allows independent game developers to develop and consume standardized clinical signals while providing a native calibration layer to accommodate the diverse physical limitations of patients, such as those in geriatric or post-stroke care.

2. Problem and Related Work

The evolution of telerehabilitation games has been historically tied to specialized depth-sensing hardware. While systems like *VirtuAlter* [de Medeiros 2018], *VirtualPT* [Heiyanthuduwa et al. 2020] and *MERLIN* [Rozevink et al. 2021] demonstrated clinical success, their architectural dependence on proprietary hardware and low modularity meant that when these sensors were discontinued, robust clinical protocols became technically inaccessible to the average patient, who often relies on commodity hardware for home-based therapy.

Many advancements were made on the modularity front, providing a framework and starting point, with proofs of concept being made to validate their approach, but they are either unavailable or still depend on the hardware [Reinkensmeyer et al. 2002, Paraskevopoulos et al. 2016, Bernava et al. 2021]. *ePHoRt* [Pérez-Medina et al. 2019] provides the most robust architecture, providing extensive diagrams and including logic for adaptive difficulty, therapeutic adjustment and integration with the browser, but the dependence on the Microsoft Kinect and lack of code availability make unavailable for general use.

Currently, there are major architectural barriers in the field of serious games for health:

2.1. The Modularity Constraint

Most existing solutions suffer from a low modularity development pattern, where motion tracking logic is tightly coupled with the game's mechanics [Pardos et al. 2022]. This creates single purpose code that prevents the reuse of kinematic algorithms across different games. Furthermore, this coupling excludes creative teams and independent game designers who may lack expertise in computer vision or advanced coordinate geometry, limiting the diversity of available therapeutic content.

The extensible frameworks that provide the needed freedom of implementation for both game designers and developers focused on therapeutic metrics provide a good starting point for architectural decisions, but many issues hinder the adoption. Lack of code availability [Reinkensmeyer et al. 2002, Paraskevopoulos et al. 2016] and adherence to specific hardware [Pérez-Medina et al. 2019]; and code that requires installation to run and requires technical programming knowledge from the healthcare professional [Bernava et al. 2021].

2.2. The Calibration and Inclusivity Gap

A critical challenge in motor rehabilitation is the non-linearity of recovery. A patient recovering from a chronic stroke possesses a radically different Range of Motion (ROM) compared to a post-surgical orthopedic patient or a geriatric user with general frailty [Rozevink et al. 2021].

Existing systems frequently fail to provide a middle layer that translates absolute physical coordinates into relative ludic success. Without an architectural layer capable of normalizing movement based on individual physical boundaries, users with severe limitations may experience frustration due to "unreachable" in-game goals, which negatively impacts clinical adherence [Alfieri et al. 2022].

A major challenge in cardiac and motor telerehabilitation is the low adherence to exercise recommendations, which negatively impacts clinical outcomes such as readmission and mortality rates [Verheijden Klompstra et al. 2014]. Evidence suggests that patients are often reluctant to engage in traditional exercise, but exergaming emerges as a promising alternative to encourage physical activity through enjoyment and empowerment [Verheijden Klompstra et al. 2014]. However, for this potential to be fully realized, systems must overcome the lack of variety that often leads to patient boredom and dropout.

2.3. Web-Based Human Pose Estimation (HPE)

Recent advancements in deep learning models, such as MediaPipe and MoveNet, have enabled real-time HPE on standard RGB webcams. However, simply migrating from depth sensors to webcams does not solve the modularity problem. Our work builds upon these technologies but introduces a "Virtual Sensor" abstraction that provides a semantic, calibrated stream, allowing developers to focus on gameplay while the framework handles the clinical normalization.

3. Proposed Modular Architecture

Ideally, we would provide a framework where game designers just had to focus on making the game engaging and require the right movements; healthcare engaged developers could implement independently tested medical impairment metrics with the required medical experts; and those responsible for rehabilitation just had to choose the games, metrics and intensity for each of their patients.

With those goals, we propose the modular architecture illustrated in figure 1

Since we want as much availability as possible, the framework is web-based and developed in TypeScript to ensure type safety and ease the process of web development

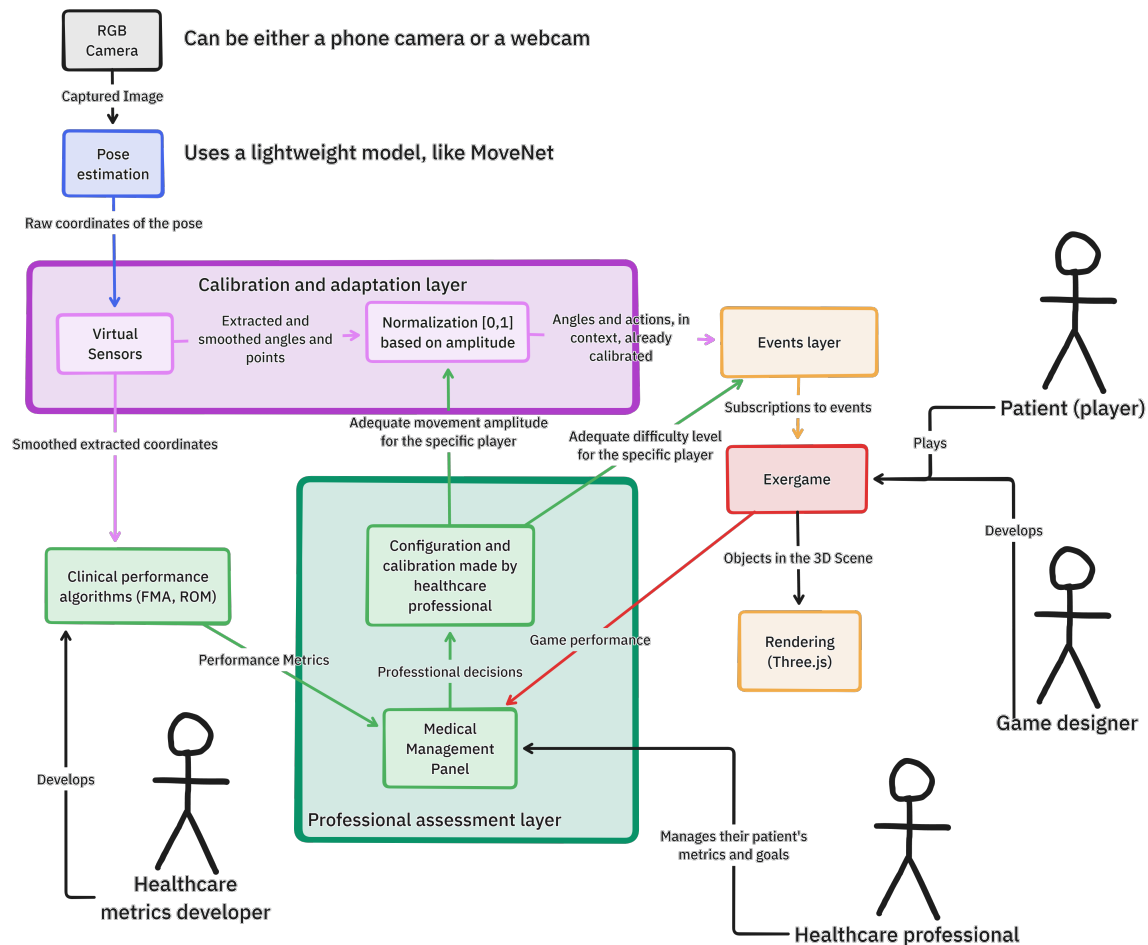


Figure 1. The proposed modular architecture: separating sensing, calibration, and gameplay layers.

for programmers less familiar with JavaScript’s peculiarities [Bogner e Merkel 2022, Haapalainen 2024].

We can describe sections of the framework as layers that execute almost entirely on the client-side (edge-native), communicating only the settings needed for the session and the results from it, prioritizing user privacy and reducing network latency.

3.1. Pose estimation

The sensing engine utilizes deep learning models, such as MoveNet or MediaPipe, to extract skeletal landmarks (right shoulder, left ankle, etc.) from standard RGB video streams. Unlike depth-dependent systems, this layer is designed to run in any modern browser using TensorFlow.js, ensuring that the framework remains accessible to patients who do not possess specialized hardware. To maintain therapeutic immersion, the layer is optimized to provide real-time tracking with low latency profile. [Pardos et al. 2022]

3.2. Calibration and adaptation layer

This layer acts as the mathematical bridge between physical effort and digital success. First, we apply temporal smoothing to the movement of the points using an algorithm such as the One Euro Filter to reduce the jitter inherent to various image capturing

scenarios. Then, raw coordinates (S_{raw}) are transformed into "Virtual Sensors" through a mandatory calibration phase. This phase is essential because motor recovery is non-linear; a stroke patient may have a significantly restricted range of motion compared to a healthy individual [Gómez-Portes et al. 2021].

The system maps the patient's individual minimum (ROM_{min}) and maximum (ROM_{max}) reach into a standardized success scale ($S_{norm} \in [0, 1]$):

$$S_{norm} = \frac{S_{raw} - ROM_{min}}{ROM_{max} - ROM_{min}} \quad (1)$$

By normalizing movement, we ensure that clinical progress is measured relative to the user's specific capabilities, fostering inclusivity and preventing frustration in early-stage recovery.

3.3. Events layer and Rendering

The final parts focus on rendering and engagement using Three.js for 3D environments [Pérez-Medina et al. 2019]. The normalized kinematic data is broadcast via a custom Events layer. This abstraction allows independent game developers to subscribe to high-level events, such as "90% right arm extension", without requiring expertise in computer vision or coordinate geometry. This separation of concerns is what enables a diverse ecosystem of games to run on a single, clinically-validated sensing foundation.

This layer also gives access to the difficulty settings set by the healthcare professional, requiring the game designer to provide ways to fine tune three high level adjustments: speed, frequency of goals and frequency of obstacles. These provide an additional possibility to keep the patient engaged, as the healthcare professional will more personally know how frustrated or excited the player gets through their normal appointments.

Our framework's modularity specifically addresses the need for diverse therapeutic content. Since mastery of a game and its enjoyment are key factors in sustained use among older adults, creating a library of various short-duration games can prevent the loss of interest observed in long-term programs [Verheijden Klompstra et al. 2014]. The standardized Events layer enables independent teams to rapidly develop these varied experiences, giving more options to achieve the high adherence necessary for effective rehabilitation in home settings [Verheijden Klompstra et al. 2014].

3.4. Professional assessment layer

This is the command center where the healthcare professional will be able to see how the patient is performing both in terms of the game (goals and obstacles) and in terms of clinical rehabilitation. They will be able to choose which metrics are relevant to the treatment, such as maximum range of motion and Fugl-Meyer Assessment (FMA) [Tannús et al. 2026], which game or games will be available and fine tune the difficulty presented to the player.

This will be available in the form of a web page in the style of a normal admin panel. A back-end is needed for authentication and database storage. The only

communication and storage occurs on those three moments: the moment the player starts a game session, the moment it ends and whenever the professional is checking how the patient has been going. Furthermore, very little data is transmitted on the end of the session, since the metric extraction occurs on the patient's device, on the first layer after the image is captured and is never stored, ensuring maximum privacy.

4. Expected Results and Discussion

Preliminary performance tests conducted during the development phase indicate that the framework achieves stable frame rates above 30 FPS on mid-range mobile devices and standard laptops. While dedicated depth sensors like the Microsoft Kinect offer higher precision in Z-axis tracking, our web-based approach drastically lowers the entry barrier by providing a "zero-install" environment.

We expect that some safeguards have to be implemented on the game logic to ensure the performance metrics are extracted correctly, such as prompting the player to keep their palm facing up to ensure that the elbow angle is captured perpendicularly to the camera and requiring the player to stand sideways when implementing games challenging front-to-back balance.

By simplifying the setup and offering a modular game layer, the framework aligns with clinical findings that exergaming is safe and feasible for elderly patients with cardiac and motor impairments [Verheijden Klompstra et al. 2014]. We expect that the ability to quickly deploy varied game modules will maintain the high adherence levels and the expectation of promising results reported in other interventions, particularly those focused on modularity, such as *Proteo* and *ePHoRt*, transforming home-based therapy into a more connected and motivating experience.

Although webcam-based tracking may have lower raw precision, the gain in accessibility and developer independence (modularity) outweighs the possible precision limitations in a telerehabilitation context. Furthermore, the mandatory calibration phase addresses the "complexity of setup" identified as a major barrier for elderly home-care.

5. Conclusion

This paper presented a modular architecture designed to combat the low adherence levels in telerehabilitation by enabling a rapid-prototyping ecosystem for diverse serious games. By decoupling motion inference from game logic, we address both the coupling of the games to the legacy hardware and the clinical need for varied, engaging content that prevents patient dropout [Verheijden Klompstra et al. 2014].

The integration of a native calibration layer ensures that therapeutic success is inclusive, adapting the digital challenges to the specific physical limitations of each patient. Our preliminary results demonstrate that a "zero-install" web approach is technically viable, maintaining stable performance for real-time feedback on commodity devices. Future work will focus on the clinical validation of the framework with post-stroke and geriatric patients to evaluate long-term adherence.

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