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Investigation on the use of Smart Contracts, based on the blockchain paradigm, in healthcare, especially in physiotherapy and rehabilitation

1 INTRODUCTION

Over the years, manual activities developed and performed by human beings have been digitized and automated by computers. This process of digital transformation and adaptation decreases the dependence on human reliability, reduces costs and minimizes impacts from unpredictable nature phenomena. As a reflection of this technological development, daily activities, such as sales, can also happen digitally through the Internet.

Though virtual environments may provide ease and many advantages, the process is not rethink to happen digitally; it turns out to be a mirror of the steps that would occur on-site. According to Nakamoto [1], online transactions are part of a system based on trusting that middlemans will guarantee security to the parties involved.

Taking into consideration the weaknesses of the current system [1], an alternative was developed: Cryptocurrencies. Emerging in 2008 with the advent of Bitcoin [2], they are a promise of an "electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party" [1].

In this scenario, the blockchain is the concept responsible for guaranteeing the operation of the system, acting as the ledger for the transactions and assuring reliability through factors such as: Hash cryptographic function, digital signatures and consensus algorithms [4], without needing a central regulatory entity [5] to whom the transactions must be reported and validated.

Bell et al. [7] affirms that despite the focus on financial services, there are several other areas where blockchain can be applied disruptively, some of them being: Elections, supply chain management, healthcare, and smart contracts. Nick Szabo [8] introduced the concept of smart contracts as "a computerized transaction protocol that executes the terms of a contract." He also defines a vending machine [8] as a canonical example: If a user has enough money, they insert it into the machine, select a product, and receive the change, thus concluding the contract. There is also the possibility of punishing one of the parties [9] if the clauses are interrupted or not properly fulfilled.

In view of the previously presented disruptive innovations, this research aims to investigate how smart contracts, through the blockchain paradigm, can be applied in healthcare, with focusing especially in physiotherapy and rehabilitation.

1.1 Blockchain

Created by Satoshi Nakamoto to be the foundation which Bitcoin runs on, blockchain is an open information ledger formed by a chain of data blocks that are interconnected through a code generated by a hash function. Since its data is available publicly, all participants of the chain have read access to the data inside a block. Its main characteristics are: Decentralization, persistence, anonymity and auditability.

The concept was developed to address the high dependency on external agents to complete monetary transactions. For its development, the following factors (but not limited by them) were taken into consideration [1]: Transactions validated by financial institutions are not completely reversible, thus being susceptible to frauds (such as double spending, a scenario where the same funds are used twice), high value additional taxes, slow process, among others.

A block is created at the moment a transaction is validated, and it is constructed from the following parameters [10, 11]:

- **Version**: System Version;
- **Nonce**: Random number, acting as a support for systems that make use of Proof of Work;
- **Timestamp**: Moment that represents the date and hour which the block was created
- **Previous block hash/digest**: Hash-function generated code that references the block created before the actual one;
- **Bits**: Size of the block, in bits;
- **Merkle Root hash**: Hash code of a Merkle Tree, that contains hashes from other transactions [11].

In order to add blocks to the chain, blockchain utilizes consensus algorithms. Although many exist, the most common variations at this time are:

- **Proof of Work**: Participants of the chain, often referred to as "miners", solve a mathematical problem [12] until the solution value is equal to the block's nonce;

- **Proof of Stake**: The block must assure it has sufficient funds to spend for this specific transaction. In this algorithm, this is done by sending the desired amount to itself. The participants are chosen from characteristics that differ from the Proof of Work algorithm, and the details of the implementation might depend on the cryptocurrency being used.

Regardless of which consensus algorithm is being used, a hacker should only be able to fraud a transaction by controlling 51% of the chain. In any scenario, purchasing enough computational power to do so in a properly established blockchain should be severely high, making it more viable if the hacker decided to participate fairly. In a chain that is starting out, or only has few users, the actual value of the cryptocurrency might be low enough to configure a loss to the attacker.

There is a scenario in which two users can produce a block referring to the same transaction, at the same time. In this case, a fork occurs. These parallel ways follow validating transactions until one becomes longer than the other; the shorter one is then discarded and the transactions present there are sent back to the validation pool, while the former is properly added to the chain.

Zheng et al. [3] states that there are two more types of blockchain: Private and consortium. While the latter only gives information access to some members of the chain, the former centralizes information access and/or validation power to a single entity. Regardless, both concepts go against the initial definition of this technology.

1.2 Smart Contracts

According to Szabo [8], a contract is a set of promises that, traditionally, formalize a relationship. By defining a smart contract as a set of contractual clauses that can be embedded in hardware and software, he states that the capabilities of a smart contract are beyond the previously mentioned canonical example of the vending machine, as its dynamism and proactivity do not rely on third parties involved.

An example that could be brought into reality in modern days are smart contracts embedded into a car computer system. Supposing a vehicle was bought on an installment, the system can prevent the ignition from starting if the payments are already due; in the same manner, it is able to delete this check from its memory if the installment is complete. Szabo [8] states that this method is cheaper and more efficient than dealing with third parties, such as lawyers and tows.

Kemmoe et al. [13], mentioning Szabo, affirms that a smart contract aims for the following objectives: observability, verifiability, privity, and enforceability. Observability refers to being able to monitor the performance of a contract, or to prove its performance to another party involved. Szabo [8], still, mentions that fields, such as accounting, put emphasis into making contracts that are transparent in such a way.

Enforceability states that, upon executing a smart contract, both parties have agreed to its clauses and should be aware of their duties, and, once initiated, it does not need action from any third party to stop its execution. It must be completed to be considered legal, while also being necessary taking into consideration the local jurisdiction where the parties are located.

Verifiability is the ability of a judge of law to check the state of the contract [8]. Finally, privity concerts the privacy of participants, as only authorized parties should have access to it.

Furthermore, according to Raskin [14], smarts contracts can be divided into two: Strong and weak. Strong smart contracts require a high maintenance cost for any legal modifications that might be necessary after its execution, while weak smart contracts can be modified with ease after its execution.

The concept of smart contracts can easily interact with blockchain and its applications: Read-only permissions guarantee immutability and, consequently, secure the involved entities. It is important to note that any necessary modifications imply the creation of a new contract, rather than modifying an existing one present in the chain.

1.3 Ethereum

Based on blockchain and smart contracts paradigm, the Ethereum platform was created in 2015, aiming at the creation of a protocol for the development of decentralized applications through a turing complete programming language embedded on its own blockchain [10], while also having its own cryptocurrency: The Ether. Despite being based on the initial concepts of blockchain, Ethereum defines itself as a distributed state machine, rather than a distributed ledger, which is the case in cryptocurrencies such as Bitcoin [18].

With the principles of simplicity, universality, modularity, agility, and non-discrimination [10], the platform seeks to give programmers freedom to develop smart contracts in various different languages, which are then converted and read by the machine as binary codes called "Ethereum Virtual Machine Code" or "EVM code," executed by the "Ethereum Virtual Machine" (EVM).

The EVM is a state machine represented by a data structure called Merkle Patricia Trie, responsible for maintaining all platform accounts linked by hash codes in such a way that they can be reduced to a single root stored in the chain [18]. The transactions are instructions cryptographically signed by the participating accounts and are executed through the EVM, resulting in two different outcomes [18]:

- **Contract Creation**: Transactions that result in a new contract, containing the compiled bytecode of a smart contract;
- **Message Calls**: Function calls to a contract to execute its bytecode, applying the compiled contract.

Applications developed using the platform are called Decentralized Apps (DApps), whose back-end, consisting of a smart contract [19], is executed on a peer-to-peer network, while the front-end can be hosted on either centralized or decentralized services. According to [15], there are already more than three thousand applications operating in this way. In [19], it is stated that a DApp is composed of the following characteristics:

- **Decentralization**: They operate independently and cannot be controlled by groups or individuals. Although often seen as an advantage, this makes the maintenance and update of applications already present on the network more difficult;
- **Deterministic**: Able to perform exactly the same, regardless of environment;
- **Turing Complete**: Execution of any action, as long as they are programmed to do so;
- **Isolated**: They are executed on the platform's virtual machine. This prevents any bugs or programming errors from directly impacting the chain's performance.

Smart contracts can be written in multiple languages that serve for this same finality, with Solidity and Vyper being the most active [20]. To ensure the sustainability of the network as well as to incentivize the participation of miners, Ethereum uses a concept called "gas fee", which is the application of a fee (paid in Ether) on any transaction, to serve as a reward for the miner responsible for validating the block representing that transaction [21]. The cost of "gas" is proportional to the computational power required and the complexity of that specific smart contract, and it can be calculated before it is deployed to the chain.

Instructions of a smart contract are composed of a series of opcodes present as EVM instructions. According to [18], a smart contract is capable of executing simple instructions such as XOR, AND, ADD, and SUB, as well as some related to stack manipulation in blockchains, such as ADDRESS, BALANCE, KECCAK256, BLOCKHASH, among a few others.

Currently, the platform is transitioning from the Proof of Work consensus algorithm to Proof of Stake, in a process known as Eth2 [22] or Ethereum 2.0. For this decision to be taken, the following present issues were taken into consideration:

- **High Energy Cost**: The mining process consumes a fair amount of electricity, and a significant portion of it is wasted [23]. In the Proof of Stake process, validators are nodes with the highest monetary power in the network;
- **High Entry Barriers**: It is necessary to have substantial computational power to participate in the current validation process and earn rewards. With the Proof of Stake algorithm, participation is possible with a lower investment in hardware;
- **Risk of Centralization**: In the current model, there may only be a few nodes capable of competing, leading to the centralization of the validation process among them. However,

according to [24], Proof of Stake is also susceptible to long-term centralization, making it necessary for the development or adaptation of another algorithm to address this issue in the future.

The possibility of using Ethereum as a base for the creation of a private network is viable, as stated in [25]. In this new scenario, the nodes would not communicate with the main network, which allows the application to run under a different set of rules and consensus algorithms. Due to this flexibility, DApps developed using the platform can range from new cryptocurrencies to games [26], and also allow for the creation of test environments for the computational power of smart contracts.

1.4 Blockchain and Smart Contracts on healthcare

The Ethereum platform proves that the implementation of smart contracts in the blockchain system is feasible and functional. However, according to Christidis et al. [6], before integrating it in healthcare, there are several issues that must be addressed.

When compared to a centralized database, due to its modus operandi, it is usual for blockchains to perform slower [6]. Furthermore, following its initial concept, all blockchain transactions must be open so that network participants have access to their data. In this scenario, since the keys are also publicly available, it is possible for a malicious user to track and, through behavior patterns, personally identify a participant.

However, modernizing this type of service also comes with several advantages. According to [16], one of the benefits associated with this development is improved quality in medical service delivery along with reduced operational costs for organizations. In the current state of the art, healthcare is expensive and inaccessible for a portion of the population, especially in countries without a public healthcare system. Additionally, allowing patients to decide which information can be shared brings transparency and increases the trustworthiness of organizations and their stakeholders [17].

Immutable records allow the tracking of drug manufacturing supplies, or even the movements between producers and distributors This not only has a positive impact on logistics but also on the healthcare sector as a whole, potentially reducing, or even, eventually, stopping, the counterfeiting and misappropriation of medications, supplies, and other items [27] that are of extreme importance to hospitals and clinics.

The work developed by [28] can be attested as a reference for the application of these technologies, as they propose a proof of concept related to a vaccination flow through smart contracts for recording consumers, available vaccine, administration and checkout.

The work developed by [29] presents an electronic health records management system using the Ethereum blockchain platform as a foundation, proposing a private network for use in neurorehabilitation systems through a collaborative model that includes patients, healthcare companies, along with educational and research institutions. In this work, patients choose which information to share and with whom, recording new sessions as after they occur.

2 RESEARCH GOALS

2.1 Main Goal

Investigate works that make use of smart contracts, based on the blockchain paradigm, in applications within the healthcare field.

2.2 Specific Goals

Investigate works related to the blockchain paradigm concerning its concepts, functionality, tools, development languages, environments, and applications; investigate works related to smart contracts, particularly on the Ethereum platform, concerning their concepts, functionality, tools, environments, and applications; investigate works that showcase applications of smart contracts in the blockchain paradigm within the fields of physiotherapy/rehabilitation.

3 METHODS

A systematic literature review was conducted on the following topics: blockchain, smart contracts, blockchain on smart contracts, and Ethereum. The searches were performed using the following search strings: (i) health data, healthcare cryptography; (ii) blockchain healthcare; (iii_ blockchain data sharing; (iv) healthcare data consensus; (v) smart contracts; (vi) ethereum; utilizing sites such as IEEE, Google Scholar, and ResearchGate to obtain the articles.

Only articles relevant to the general topic studied or that provided technical information about the functioning and/or state of the art of blockchain systems, healthcare, and the Ethereum platform were included. Since it was often found that works only contained a brief summary of these technologies, rather than an in-depth explanation about them, gray literature from reliable sources (such as the whitepaper provided by Ethereum itself) were used as supporting materials. Another inclusion criteria was that the articles must have free access.

To ensure a theoretical basis consistent with the current state of the art, any materials prior to 2015 were discarded. However, the explanation written by Nick Szabo, the creator of the concept of smart contracts, as well as the whitepaper by Satoshi Nakamoto on Bitcoin, both dated before the inclusion date, were kept, as these were responsible for the creation of two concepts vital for this research. The materials were divided into the following categories:

Category	**References**
Foundation on Blockchain	Bitcoin: A Peer-to-Peer Electronic Cash System [1] An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends [3] COMO funciona o Proof of Work na blockchain do Bitcoin [5] Introdução às tecnologias dos blockchains e das criptomoedas [10] BLOCKCHAIN: Prova de Trabalho (POW) x Prova de Participação (POS) [12] Cryptocurrencies and blockchain: Legal context and implications for financial crime, money laundering and tax evasion [23]
Foundation on Smart Contracts	Blockchains and Smart Contracts for the Internet of Things [6] Smart Contracts: Formalizing and Securing Relationships on Public Networks [8] A Survey on Security Verification of Blockchain Smart Contracts [11] The Law and Legality of Smart Contracts [14]
Foundation on the Ethereum platform and its technologies	UMA Plataforma para Smart Contracts e Aplicações Descentralizadas da Próxima Geração [9] ETHEREUM VIRTUAL MACHINE (EVM) [18] INTRODUCTION TO DAPPS [19] SMART CONTRACT LANGUAGES [20] GAS AND FEES [21] PROOF-OF-STAKE (POS) [22] e-PoS: Making Proof-of-Stake Decentralized and Fair [24] PRIVATE NETWORKS [25] Which Crypto Projects Are Based on Ethereum? [26]
Blockchain and/or Smart Contracts applied to healthcare	Using Blockchain for Electronic Health Records [4] Applications of Blockchain Within Healthcare [7] Improving Healthcare Processes with Smart Contracts [16] Dynamically integrating electronic-with personal healthrecords for ad-hoc healthcare quality improvements [17]

	Blockchain for drug traceability: Architectures and open challenges [27] Modelo de negócio para saúde colaborativa usando smart contracts: caso TokenHealth [28] Blockchain para gerenciamento de prontuários eletrônicos [29]

4 RESULTS AND DISCUSSION

Even though works especially aimed at rehabilitation and physiotherapy are scarce, analyzing the concepts presented in previous readings, categorized as "blockchain and/or smart contracts applied to healthcare", provides a general overview of the role of these technologies in a similar ecosystem.

Taking into consideration the works so far, it is plausible to assume that a blockchain integrated with smart contracts would be capable of providing protection to patients, as any health report could be recorded on the chain and, depending on the arguments that would lead to the creation of the block, be easily auditable. This would bring ease into identifying doctors and/or other health-related professionals that might have made procedural errors or prescribed incorrect medications and/or treatments without scientific foundation for patients.

4.1 Technologies

As proposed initially by [29], a collaborative network that includes healthcare-related companies, along with educational and research institutions would be the ideal members to start the ecosystem, as data sharing among them is beneficial for all parties involved.

The creation of a private network based on Ethereum 2.0, employing the Proof of Stake or Proof of Authority consensus algorithm, would avoid the need for external members to act as miners and would also allow participating institutions to avoid spending money or hardware that could be allocated for other purposes. Additionally, since it is a private network, gas fees could be reduced or discarded depending on the consensus algorithm used. The use of an internal cryptocurrency or delegation of authority to each institution would be up to the healthcare company owning the blockchain, according to their needs, without excluding the possibility of creating a custom consensus algorithm.

The blocks could be composed of:

- **Timestamp** (date/time when the block was created);
- **Previous block hash;**
- **Bits (size)**;
- **Merkle root hash**;

- **Patient key** (identifier pointing to a specific position in the database related to the patient's electronic health record);
- **Doctor key** (identifier, equivalent to a CRM number – Brazilian identifier for medical doctors –, that allows identification if there is access to the institution's database).

For this scenario, the above items were chosen taking into consideration the auditability of the block as the most important factor.

When a medical session is scheduled, a smart contract would be generated, and it would start being active on the agreed-upon days. The patient would then receive a validation token (similar to what is done in some health insurance plans in Brazil) and the contract would change its status based on clauses related to the validation of this token. It could grant the doctor exclusive access to the patient's electronic health record or terminate the appointment if the token was not validated (within a specified time) or was validated negatively.

After the modifications are saved, the block is created and sent to the network for validation. It is noted that the block does not store any data other than the items described previously; it only serves as a record of the approximate date/time of the modification, as well as the destination patient and the originating doctor. Any changes made to the health record are not reflected in the block.

At the end of the contract, the *selfdestruct* opcode is called to remove it from the chain, making it necessary to create a new smart contract in case any modification is necessary

4.2 Data Transparency

Patients should be able to customize data access permissions at any time, choosing what they want to be shared and which organizations can access it. Additionally, organizations need to be transparent in data collection, as emphasized by [17].

4.3 Data Sharing with external entities

Data should be shared in a way so patients are anonymous. Techniques, such as anonymization and noise insertion, can be enforced for this purpose. Additionally, it is preferred that access to data means that it is retrieved from where it is stored, rather than being a direct access to a database.

5 CONCLUSION

Blockchain and smart contracts are technologies that date back over a decade. Even though there have been successful implementations, such as in Estonia, it is only in recent years, after the popularization of cryptocurrencies, that the integration of these technologies into various fields began to be studied. However, studies focused on healthcare tend to be general system proposals or systematic reviews, making more specific applications still scarce.

However, it is clear that the benefits brought by the integration of these technologies are significant, marking an important step towards the modernization of systems in an era where access to information and data sharing must be transparent.

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