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APPLICATION OF BIG DATA ANALYSIS AND INTERNET OF THINGS TO THE INTELLIGENT ACTIVE ROBOTIC PROSTHESIS FOR TRANSFEMORAL AMPUTEES

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ABSTRACT

With the advent and rising usage of Internet of Things (IoT) eco-systems, there is a consequent, parallel rise in opportunities where technology can find its place to improve a number of human conditions. However, this is nothing new - we have been perfecting the usage of tools to aid our daily living throughout history. The true evolution lies in the interaction between us and the tools we create. Tools are now smart devices, yielding an opportunity where human-device interaction is giving us the very knowledge on how to improve that particular synthesis. From improving our fitness to detecting bradycardia and response of traumatic brain injury patient, we have come to a point where we are able to gain actionable insight into a lot of aspects of our health and condition. This creates a certain autonomy in understanding the unique make-up of every single person, in addition to yielding information that can be used by health practitioners to help in diagnosis, determination of medical approach and right recovery and follow-up methods. All of this supported by two major factors: IoT platforms and Big Data Analysis (BDA).

This paper takes a deep dive into exemplary set-up of IoT platform and BDA framework necessary to support the improvement of human condition. Our SmartLeg prosthetic device integrates advanced prosthetic and robotic technology with the state-of-the-art machine learning algorithms capable of adapting the working of the prosthesis to the optimal gait and power consumption patterns, which provide means to customize the device to a particular user.

KEYWORDS

human-machine interface, active robotic prosthesis, machine learning, big data analysis

1. INTRODUCTION

At the surface, the IoT eco-system consist of the following components: sensors, hardware device, people, and internet connection that enables data transmission between a subset of the above-mentioned components. Sensors are used to capture any physical or biometric event and convert it into electrical impulse that is then used to create a reading. Depending on the IoT system, there is also a presence of actuator, which reads the electrical input and executes a specific action. Data captured by sensors is routed to IoT gateway, a device that acts as an intersection for routing the data in-between intranet (a local network between sensor and actuator bearing hardware and accompanying smart devices) and internet (data that is sent to a cloud platform that enables long-term storage and processing of the said data). Data

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transmission to Internet is crucial component in extending IoT Platform with BDA capabilities.

To support these capabilities, a common approach is to setup a Cloud framework which consists of database that stores the captured data, data orchestration solution to enable data movement and prepare it for transformation and analysis. From that point on, a set of data products is created, either for product improvement purposes or to send actionable insights to the users of the IoT product in order to help them achieve their goals or improve the usage experience.

To help understand the entire framework and workflow, the following example describes one of the use cases of IoT and BDA application in e-health sector. In order to make-most of physical activity, while preventing a risk of exertion, a person gets a smart bracelet that tracks heart rate. Once it is being worn, the bracelet uses a LED light to make veins visible to the sensor that measures the velocity of blood pumping. Sensor sends captured data to the embedded gateway, where readings are sent to a bracelet-paired smartphone, usually over a Bluetooth network. At that point, the app installed in the paired smartphone sends the data to the Cloud server where data is being stored long-term. From there, the data can be sent to distributed file system, such as Hadoop, to enable data processing (distributed file systems have for a while now, been a go- to solution for fast, even real-time Big Data processing). At this phase, the data is being used to create a specific set of reports to detect patterns, anomalies and trends, or create aggregated summaries that are being sent back to users via Application Programming Interfaces (APIs) for insights and completed activity summary. Used long-term, this eco-system provides valuable information to user, such as safe-training range, performance metrics based on heartrate, pace, weather conditions, etc. Further sophistication of such eco-system can provide alerts on approaching over-exertion, resting period and post-workout recovery data, in addition to highly specialized and personalized tips on improving the results and maintaining good cardiovascular condition.

2. RELATED WORKS

Scientific and technical innovations have made a significant progress towards developing more comfortable, efficient and lifelike artificial limbs. Future progress is likely to depend on the interaction between three powerful forces: amputee’s demands, advances in surgery and engineering, and healthcare funding sufficient to sustain development and application of technological solutions. Prosthetic technology has advanced to a remarkable degree in the past two decades, driven largely by amputees’ demand. Today, otherwise healthy individuals with transfemoral amputation should be able to participate in a full range of normal responsibilities, to walk without any perceptible limp, and to engage in recreational and sports activities [1].

In developed countries the main cause of lower limb amputation is circulatory dysfunction. The prime reason for this is atherosclerosis; although up to a third of patients have concomitant diabetes. These people are usually in their sixth decade (or older), and most have additional health problems that limit their walking ability [2]. This is in sharp contrast with developing countries, where most amputations are caused by trauma related either to conflict or to industrial or traffic injuries [3]. The devastation caused by land mines continues, particularly when displaced civilian return to mined areas and resume agricultural activities [4]. Global extrapolations are problematic, but a recent US study states that the amputation rate among combatants in recent US military conflict remains at 14-19 % [5].

The single most critical aspect of any prosthesis is the quality of the interface between the limb remnants (stump) and the artificial prosthesis. The portion of the prosthesis that fits snugly over the limb remnant, the ″socket″ determines the amputee's comfort and ability to control the artificial limb. Since the 1980s prosthetic clinicians and researches worldwide have made breakthroughs in design and materials that have greatly improved the connection between the socket and stump. Currently, silicone elastomers are widely used to create a soft and slightly

elastic inner liner, providing a thin, comfortable, and compliant barrier between the amputee's skin and the more rigid, weight bearing portions of the prosthetic socket [6].

Recently researchers have developed a variety of thicker gel materials that add a measure of cushioning and pressure dissipation while retaining the benefits of the original liners. Carbon fibre composites, developed by the aerospace industry, are increasingly being used in the artificial limbs, largely because of their superior strength to weight characteristics. There are currently a large number of different design solutions of the above–knee prosthesis, by which searches are trying to enable and make an easier walking for limb amputees. It is attempted to make above-knee prosthesis movable end enable its easier use. Large attention is directed towards finding the best construction of mechanical joint of knee and ankle. Helped by suitable medical therapeutics and exercises, amputees "learn" how to walk using their prosthesis. An important example is given by the so-called "sports prosthesis" which gives maximum aid to the sport amputees in achieving first–class results [7].

The first artificial knee with an "on-board" computer to improve the symmetry of amputee's gait across a wide range of walking speed was developed by Blatchford in the early 1990s. Studies have confirmed that these "intelligent prosthesis" offer amputees a more reliable gait pattern during the swing phase of the gait cycle, permitting them to walk with more confidence and in a more energy efficient manner [8]. The Otto Bock C Leg takes this a stage further, offering not only symmetry in the swing phase but also an improved security in the stance phase. Sensors in the ankle and shin of the prosthesis continually assess the position of the leg in space as the amputee is walking. The data are fed into two microprocessors inside the knee, and the resistance from a hydraulic damper is adjusted up to 50 times a second, optimizing both the stiffness throughout the entire gait cycle [9], as well as hydraulic damping, making both walking and stair descent easier [10]. However, without the usage of an outside power source, it is impossible for the body to perform a number of everyday activities which involve climbing significant slopes. This makes radically different solutions necessary [11].

3. SMARTLEG OVERVIEW

The basic idea of our approach is to incorporate additional linear actuators into an existing prosthesis (Fig.1).

Such a prosthesis will have the capability of active movement control in knee and ankle joints through the embedded actuators, which will enable achieving of necessary flexion and extension, as well as driving of below knee and above knee components.

It is intended that embedded initiators, by using the power from an outside source, support a disabled person during stair climbing. Indeed, the biggest problem for above–knee amputees is lack of their own knee, including the lack of muscles that enable climbing. The forces normally generated in the knee during climbing are among the largest exerted in the human body and are difficult to generate in existing prosthetic legs. For that reason, an outside power source is necessary.

In addition, active prostheses can provide users with an increased degree of comfort compared to traditional passive actuators by autonomously adapting to their needs. This is achieved by employing advanced learning algorithms from the realm of artificial intelligence and machine learning that, after a short training period, adjust the on-board control algorithm to match either observed users' walking patterns (if the training set can be gathered by sampling data from the other limb), or standard motion patterns from the healthy subjects otherwise [12].

By equipping the artificial leg with standard sensors found on commercial robotic platforms, the onboard microcontroller will be able to recognize different terrains (their type and slope) and to instantaneously adapt the gait to fulfil users' expectations.

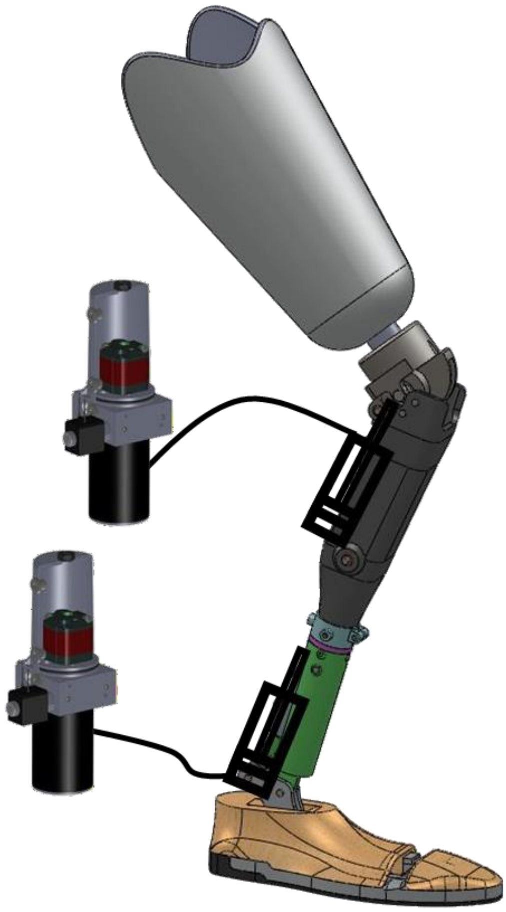

Figure 1. Model of modified above-knee prosthesis [13]

In the development of a smart active robotic prosthesis we focus on the following problems:

- development of the optimal hydraulic installation;
- development of the associated control algorithms;
- development of artificial intelligence solutions dealing with intelligent behaviour, learning and adaptation able to reproduce complex walking patterns under different conditions.

3.1. Hydraulic System

While climbing up (or climbing down) the stairs, the biggest problem for above-knee amputees is the missing knee power of the existing prostheses. For example, in the existing

electromyography prostheses the myoelectric signal is not capable of providing enough power for the above-knee prosthesis, which is the main reason why an outside power source is needed.

Previous work has the intent of defining a hydraulic system and an appropriate control system with an independent source of power supply. The hydraulics parameters of the linear actuators are based on the achieved experimental results when a load was attached to the knee joint as well as on the calculated theoretical parameters [14].

One hydraulic actuator will be installed into the prosthesis's knee to provide power to lift the weight of the body; the other hydraulic actuator will be installed into prosthesis's ankle. Both actuators will be an integral part of the same hydraulic system. Fig.2 shows a schematic of the hydraulic power generator installed in the existing SmartLeg prototype [15].

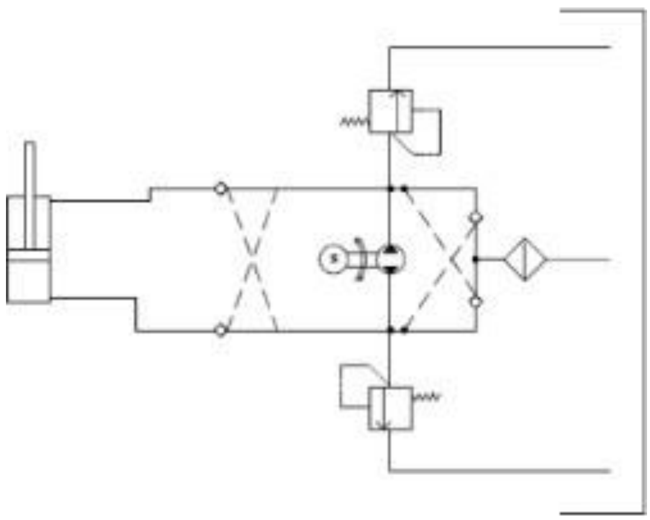

Figure 2. Model of modified above-knee prosthesis [15]

3.2. Control System

The hydraulic system must include an appropriate control system and regulative elements for directing fluid as well as distributing it towards hydraulic actuators. In the broadest terms, controls or control systems relate to any device, component, or combination of components, the resulting output of which responds to given command input signals.

Requirements for the control system are:

- to collect data of the flexion and extension angles at the knee and ankle;
- to identify the force/pressure during the contact the prosthesis has with the ground;
- to predict the leg motion/gait during the stairs climbing based on the sensory input.

Control systems may be with, or without feedback signals. The feedback control system compares the reference set-point to the transduced output and/or controlled variables. The resulting difference between these two signals, or error signal, is used to reduce the difference between the output and input toward zero.

This error signal can be amplified by means of the system components so that the system output almost exactly follows or matches the system input. Amplification of the control signal is usually required to actuate solenoid operated hydraulic valves. Electronic controllers that are designed for hydraulic applications will normally include the required amplification functions.

Spool type proportional valves will normally have a certain amount of spool overlap which produces deadband. For pressure and flow controls this deadband will occur at the start of spool movement. For directional valves the deadband will occur around the centre position. Spool overlap reduces leakage in the null position and also provides a greater degree of safety in power failure or emergency stop situations. The effect of spool overlap requires that a certain minimum signal level has to be present at the solenoid coil before any noticeable result occurs in the system.

3.3. Learning and Decision-making System

The “smart” adjective of our system refers to the ability of the robotic prosthesis to automatically adapt to the user’s current needs and to maximize its comfort in the everyday life.

These desiderata become a necessity in active upper-limb robotic prostheses in which myoelectric signals are not sufficient to provide a necessary reference input to drive the system.

In order to achieve this goal, we plan to adopt a number of advanced artificial intelligence and machine learning techniques for adapting the control algorithm to a particular user’s needs in different circumstances. To this aim, besides the sensors actively used in controlling the robotic prosthesis, we intend to equip the artificial limb with a number of low-consuming sensors commonly used in mobile and humanoid robotics such as proximity sensors and sonars for detecting the presence of stairs and eventual obstacles and their distance with respect to the user.

We plan to adopt a hierarchical control structure in which the low-level controller directly governs the variables of interest, given a reference set-point provided by an adaptive high-level controller trained to different walking patterns for a particular user.

Fig. 3 depicts the SmartLeg learning and control system [15]. Typical walking patterns in different circumstances will be learned by gathering data coming from various sensors, in particular those from the other limb. In particular, recurrent neural networks (RNN) seem a promising choice that allows learning arbitrary sequences of inputs [16]. RNNs have been successfully applied in learning motor control patterns that govern dynamical systems [17]. Similar problems have also been studied in generating motion patterns for bipedal humanoid robots [18].

Users will undergo typical training sessions in which signals coming from the sensors will form the training set upon which the weights and connections of the RNN will be built.

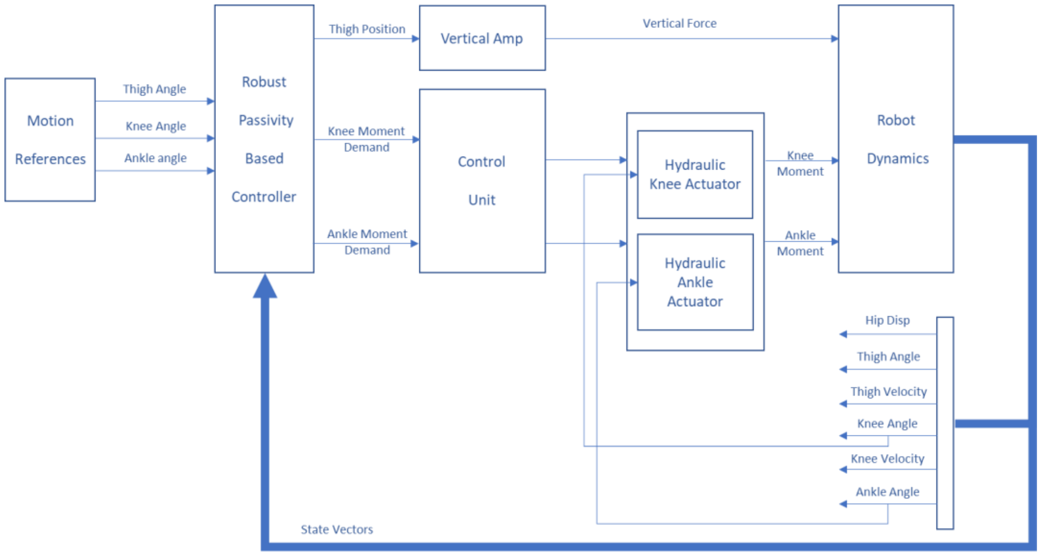

Figure 3. SmartLeg motor learning and control system [15]

Since different motion patterns are adopted in different circumstances (e.g. climbing vs. walking), we plan to train a number of RNNs – depending on the operational conditions. Particular care will be given to the stability issues of the resulting dynamic system and a number of standard safety tests will be performed with experts in rehabilitation.

In order to decide which RNN to activate at a given time, we plan to train a classifier able to recognize the current condition based on the available sensory inputs. To this aim, a number of standard machine learning techniques (e.g. Neural Networks, Support Vector Machines, Bayesian classifiers) will be tested [18].

4. Solution Approach

In order to go a step further and utilize the potential of Big Data Analytics (BDA), the challenge of connecting the prosthesis to the Internet has to be resolved.

One approach is embedding the LTE-M modem into the prosthesis itself. Choosing LTE-M technology enables direct connection to the Internet, enabling direct communication between prosthesis and servers. Additionally, it provides operational autonomy through its battery-reliant power system. However, as of March 2019, Global Mobile Suppliers Association (GMSA) has identified 60 operators based in 35 countries are investing in LTE-M networks. Out of those operators, only 34 of them, in 24 countries have deployed these solutions [19]. This in itself poses obstacle in making this prosthesis, and especially making the ‘smart’ aspect of it available in developing countries, where rate of amputees is much higher than in developed countries.

Another approach is to enable data transmission to prosthesis’ user smartphone via Bluetooth technology, in which case the data is being transmitted to a smartphone and from it to servers via WiFi / LTE networks for permanent storage. Owning smartphones has today become ubiquitous. In the period of the next six years, it is estimated that additional 1.4 billion people will become mobile internet users, amounting to a total of 5 billion users [20]. Based on this data alone and expected growth of unique smartphone owners in the world, choosing

Bluetooth technology is the step in the right direction. What differentiates prosthetic limb from other IoT devices that require constant connection to Internet is its attachment to a person, hence, user's

mobility determines, creates, or takes away the opportunity for prosthetic limb to be connected, unlike other IoT products that are fixed in a single location with stable Internet access. However, future deployments of the LTE-M networks globally will allow switch to the LTE-M technology, enabling the creation of the true IoT eco-system for the SmartLeg prosthesis.

Having a prosthetic limb that is able to communicate with WiFi / 3G / LTE enabled device leads us to a next phase, which is developing smartphone application that will communicate with prosthesis and feed the data to a data centre. The following diagram demonstrates the communication cycle of the entire eco-system (Fig. 4), from key component level.

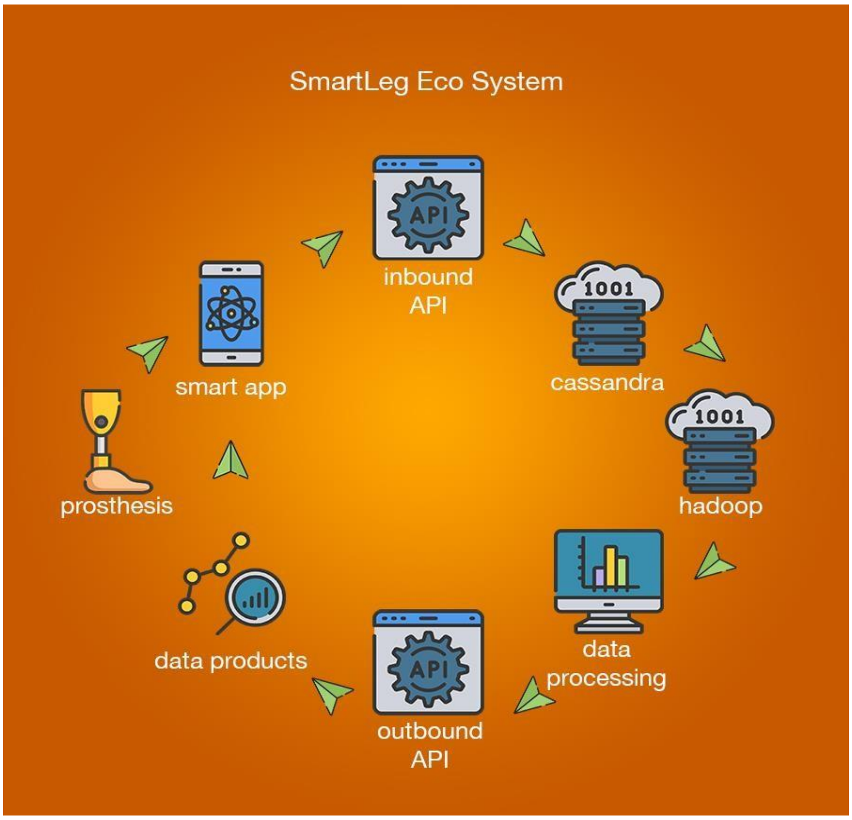

Figure 4. Communication cycle of the SmartLeg eco system

The concept behind smart application is the usage of Bluetooth protocols that enables pairing smartphone with prosthetic limb and with it, data transmission between limb and smartphone. This allows further control in formatting the data coming from prosthesis' sensors and actuators into interpretable and analytics-friendly format. At this point, smartphone application sends the obtained data to Application Programming Interface (API) from where it is stored permanently in NoSQL database, such as Cassandra [21]. Choosing NoSQL database additionally allows optimal transaction transmission over API.

From that point on, data is being transmitted to a distributed file system, e.g. Hadoop [22], which makes it easily accessible for finer and broader analysis, without compromising the original records stored in Cassandra. This analysis yields range of data products, including but not limited to summarized reports, training datasets, and personalized tips for prosthesis users. The proposed system setup has these data products residing in Hadoop, which can be propagated directly back to users, again via API.

5. BDA CAPABILITIES

Extending the prothesis with these capabilities begs multiple questions on usage of that data. The following use-cases have been identified as crucial:

- Use case 1: Analysis of the biometric data will help provide the insight into the state of the prosthesis user- her/his exertion, stress on cardiovascular system and hence the comfort and confidence in using the artificial limb.
- Use case 2: Analysis of the motion data generated by the prosthesis usage. This will enable the pattern-matching analysis and successfully determining the gaps of the individual usage experience compared to the training data set. Ultimate goal of this use-case is to remove the gap altogether and provide user with optimal experience based on hers/his individual make- up (pace, weight distribution, stability, etc.)
- Use case 3: Motor and device data analysis will provide knowledge of usage stress on the prosthesis itself, which will in turn help with identifying potential device failures and provide proactive instead of reactive approach to securing the best possible quality of its components and overall usage.
- Use case 4: Data insights obtained from use cases 1, 2 and 3 will be communicated to field- experts which will in turn provide guidance in perfecting the entire prosthesis eco-system, from its individual components, analytics capabilities and users' experiences.
- Use case 5: The processed, analysed, and summarized data (in form of individualized tips and expert advice) will be sent back to individual users to help guide their day-to-day activities and ensure they themselves have daily, and ultimately, near real time actionable information that will additionally provide them with autonomy and confidence in 'learning' to walk again.

6. RESULTS AND ANALYSIS

In the following diagrams we are presenting the lower limb trajectory while simulating climbing on the first tread of a staircase (Fig. 5 a). The trajectory diagram of the healthy subject is serving as a reference.

In Fig. 5 (b) the trajectory of the prosthetic leg is observed and presented for the case where only a adaptive feedback controller is implemented. Some discrepancies can be observed when compared to the reference case.

In Fig. 5 (c) the trajectory of the prosthetic leg is presented. In this case the motor data captivation and learning has been implemented. It can be seen that it leads to better and faster tracking than in the case of adaptive feedback controller.

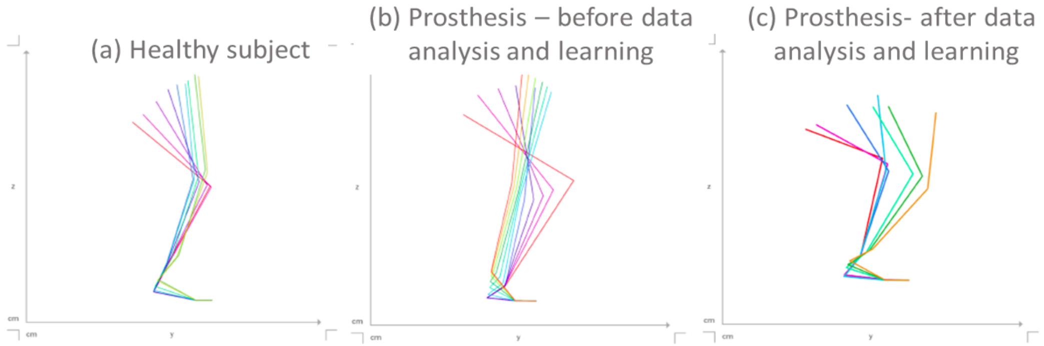

Figure 5. Reference trajectory tracking for a prosthetic leg; (a) healthy subject, (b) prosthetic leg before and (c) prosthetic leg after data analysis and motor learning

7. CONCLUSIONS

In this paper we have presented preliminary investigations towards an active robotic prosthesis that could potentially enable people with an above- or below-knee amputation to perform different types of motions that require power in lower limb joints such as slope walking or stairs climbing.

Our prototype, called SmartLeg, combines advanced mechanical design with artificial intelligence-based adaptive control solutions. While the former aims at maximizing the functionality of the prosthesis form the engineering point of view (power consumption, stability, etc.), the latter is rather concerned with its usage.

The adoption of machine learning algorithms capable of learning and reproducing optimal motor patterns and BDA capabilities through IoT provides an increased comfort for the end user and permits to customize the device to its particular needs.

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I'm working as an Assistant Professor at the Faculty of Mechanical Engineering, University of Sarajevo. My PhD thesis was in the field of rehabilitation robotics, namely the development of an active above-knee prosthesis with actuated knee and ankle joints. The thesis focussed on solving the problem of climbing the stairs for transfemoral amputees as that is the phase which requires most external power.

Haris Velijević

Currently part of Data Engineering team at Seera Group, Dubai. I specialise in architecting and utilising data platforms as a driving force behind business transformation and consumer experiences. My contribution to the SmartLeg prosthetic device is designing the architectural framework, data products and use cases in order to provide data-driven support for prosthesis usage and experience improvements.