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Prosthetic Knee Joint -A Survey And Using Reinforcement Learning For Natural Gait

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Abstract - Machine Learning has been an area of humungous research recently, nowadays reinforcement learning is being widely used in solving gaming problems and in other domains too. Prosthetic is one such field where Reinforcement Learning Algorithms take intelligent decisions and are being use to imitate natural human movement. Amongst these prosthetic devices is prosthetic knee where the patient/amputee always long for a natural gait. Prosthetic Knee is a replacement of a natural leg which is lost due to multiple reasons such as the diabetes, peripheral vascular diseases to name a few. Number of lives which is affected by amputation is huge. The amputee is not only deprived of physical capabilities, but psychological setback. With the advent of sensor driven devices which are personalized as per the users and Artificial Intelligence being use to develop real world applications, it is believed that human life will be easy. In this paper, a survey has been done on the work done until now in developing a prosthetic knee joint and a review is done as to how Reinforcement Learning is impacting lives and being used in real time applications and out the best performing agent for prosthesis.

Keywords: Reinforcement Learning, Prosthesis, Lower Limb Prosthetic device, Model Based RL,Model Free RL

1. Survey of work in Prosthesis

The effects of a pediatric PK joint on gait were evaluated using an intelligent stance-phase lock (Andrysek et al., 2007). With an intelligent stance phase lock knee joint with unilateral amputations, the spatiotemporal parameters demonstrated higher gait speeds. In addition, the increased velocity was associated with enhanced temporal interlimb asymmetry, excessive movement range of PK in swing and joint moments and powers. Analysis was however, carried out using a limited sample size and data was obtained during only a single session with each variable and gait differences which may vary daily were also not taken into account. The need for further study using more and more complex samples has therefore been proposed to accurately establish the variations between components.

A methodology for developing a fully passive prosthetic knee mechanism, specifically for transfemoral amputees, was proposed (Arelekatti et al., 2015). It was introduced for stabilization, initial stance flexion-expansion and late swing and stance control, there was a differential friction damping system. The key aim of this study was to minimize the cost of metabolic resources and to fulfill cultural, socioeconomic need.
In comparison, for some amputees, this may increase the chances of unintended falls. In addition, the use of friction-dependent brake pads for variable damping due to wear and tear, exposure to rain and dust, and humidity fluctuations. Also in the proposed prototype uneven terrain, cross-legged seating and squatting were not addressed.

The automated stance phase lock knee joint design for the young amputees with transfemoral amputees was proposed (Ngan and Andrysek, 2009). The prime focus for this work was to use biomechanical simulation to describe the automatic stance lock control mechanism and to build a 2-axis smart prosthetic knee joint for children. The proposed framework used a limited sample size that demarcated the prototype's applicability to other prosthetic, reasons of amputation, genders and ages. There was a need to test these factors using greater quantities and realize the therapeutic benefits and drawbacks associated with the developed knee prototype was then recommended.

The biomechatronic Prosthetic knee architecture for Transfemoral Amputees was proposed (Torrealba et al., 2010). The gait classification in the proposed study was based on accelerometer signals that were analyzed using the method of event detection, but data samples and gait detection of Prosthetic knee joint in amputees was not undertaken. There is a need of continuous functionality of the device which implies that the battery power usage for longer operation and weight reducing strategies of the proposed prosthesis should be incorporated.

A study using a microprocessor-controlled Prosthetic Knee (Kaufman et al., 2007) was presented. It demonstrated that a microprocessor-controlled Prosthetic Knee joint had a greater control than the mechanical knee joint, leading to changes in balance and gait. However, in a microprocessor-controlled Prosthetic Knee, people with scarce ambulatory abilities were unable to take advantage of the enhanced technical characteristics.

(Lawson et al., 2011) The proposed controller involved three phase control like slope estimation, ground-search and impedance modulation. The prosthetic knee joint adapt quickly providing stable stance to the amputees. By gathering relevant data for a series of stance, the efficacy of the proposed controller was tested on a knee prosthesis. Although, the reasons for improving the amputee's balance and stability were not taken into account.

Adaptive Dynamic Programming used for adaptive controlling (Wen et al., 2016) of transfemoral prostheses is The main objective of this work was to achieve human gait by adjusting the parameters of impedance control by the controller in a prosthetic knee joint. Gait phases of the amputees were analyzed and the model was trained while walking to personalize user efficiency characteristics through online modification to follow the goals of individual users. This showed the ability of the dynamic programming to change the prosthesis controller to achieve natural human kinematics. But, criteria like balance load and distinct walking speed and walking on uneven terrain was not taken into account, also the amputees on which the AD controller was tested was limited.

(Sup et al., 2007) designed a powered prosthetic knee, which exhibited better functionality than the mechanical knee joint yet further improvement in the same was needed. (Lambrecht et al., 2009) presented a semi-active prosthetic knee joint which has hydraulic dampers, the training of the system was exhaustive with all the trials like climbing up and down the stairs which eventually helped in load adjustment of the prosthetic knee, however the system was not completely developed for climbing up the stair and since it was not fully active control, the factor of energy consumption has to be taken into account. (Geng et al., 2010) worked on minimizing the energy consumed by an amputee while walking in a prosthetic knee joint, though it was not fully automated system. (Simon et al., 2013) also worked on a powered prosthetic knee joint and describes about a five distinct stance phases. But the same impedance parameters were used for all the amputees and therefore essential parameter modification was needed. An intent detection algorithm was used by (Ambrozic et al., 2014) driven by wireless sensors. The finite state control of the prosthetic knee joint functioned with a motion recognition, but the study was incomplete as walking on uneven terrain was not taken into account.

Prosthetic Knee Joint was presented by (Afzal et al., 2014) . The suggested design was validated functionally. The main aim of the analysis was to build a robust, lightweight and cost-effective prosthetic knee . While it showed improved results, the incorporation of the advanced features needs more optimization. A control methodology was presented by (Inoue et al., 2016) for a stable stair ascending and stair descending and showed a stable gait but was not detailed in terms of energy consumption and stability. A model for inclined plane walking was proposed (Paredes et al., 2016) to allow the prosthesis user to cover uneven surfaces. The suggested model did not require tuning techniques to determine the gains of the controller during inclined plane walk. However to be carried out offline, one-time manual optimization was needed for plains. The solution proposed by (Goršič et al., 2014) was computationally effective and included validation rules allowing real-time computation. But for assessment, it employed a small sample size. In comparison, other activity maneuvers, such as sitting and ascending stairs, were not included. It was intended only for the purpose of a single motion i.e. walking at a stable speed .Therefore, using more samples and with other activities such as stair climbing, sitting, etc., the needs to be tested.
A technique for designing Adaptive Modular Active Leg was proposed (Nandi et al., 2009) A (AMAL). bipedal robotics technology was utilized. The goal of this work was to establish a biological motor control mechanism for an amputee. An approach based on fuzzy logic was initially used to provide an amputee with suitable gait patterns, then a technique for constructing a Central Pattern Generator (CPG) was devised. Nevertheless, more research related to less costly and energy-efficient prosthesis production needs to be carried out.

2. Introduction to Reinforcement Learning

Deep Learning or Reinforcement Learning (RL)(Sutton et al.,2018) has a spectrum of algorithms which ranges from Model Based algorithms to Model Free Algorithms, which are generally goal oriented and take decisions on the basis of trial and error. However, when we talk about real time applications ,there is less or no room for trial and error therefore the Model which is being used in these applications must be properly trained for unforeseen situations as well.RL is different from other ML techniques because of the agent's interaction with the environment with respect to every state and looking for maximizing the reward function and minimizing the penalty. There this seems to be best fit for developing an artificial knee joint wherein the algorithms are properly trained and reward functions are defined correctly so that it resembles individual's gait flawlessly.

3. RL Algorithms

The concept of value function (Barto et al.,2017) plays an important role in RL. RL is basically mapping the situations to its action which is called as a policy function. Actions are always reward driven and all the algorithms in this category are tuned in for maximizing the rewards. The agent should exploit all the previous high reward episodes and at the same time it should also explore new actions in order to take a better decision. Therefore, exploration and exploitation are always a fix and looks like an unresolvable issue while the goal still remains to achieve high rewards out of any action. Therefore, the exploitation and exploration should be well balanced. An entropy coefficient could be added to it so that to increase the randomness of the function in a limit of 0 -1.

Conventional RL system consists of Markov Decision Processes(MDP) comprising of a an action A,state S,reward R ,state transition probability as T *(s',a, s).*According to MDP,the state *s'* only depends on prior state s and action a(Sutton et al,2018) and has nothing to learn from it's history.

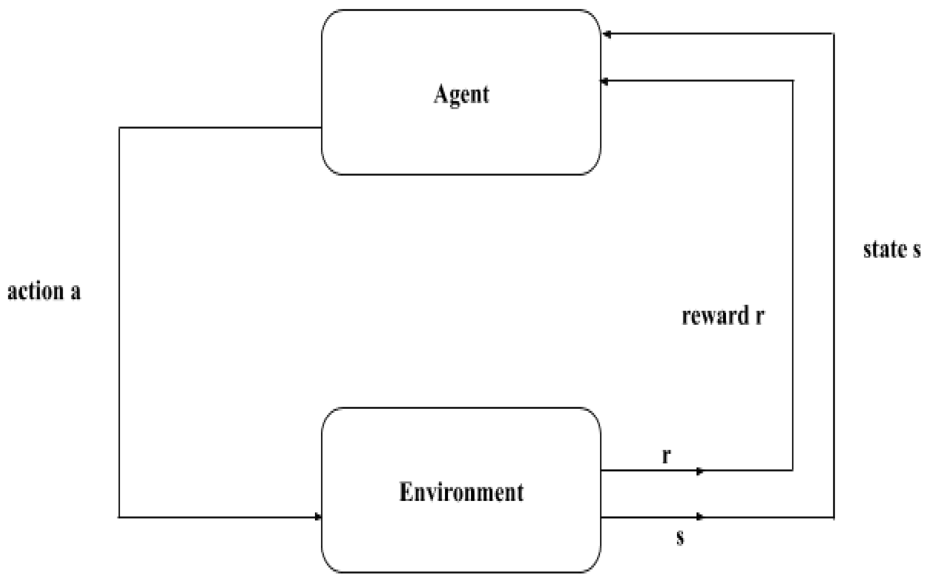

Fig 1: Component of Reinforcement Learning

4. Challenges with RL

RL,amongst all the Machine Learning techniques is referred as Trial and Error Learning, therefore the users have always been apprehensive of using the same for real time applications. Practical usage of the same has always been a question,below are the few challenges that is always associated with Reinforcement Learning.

1) As the model is trained on the simulator, learning on real time systems a challenging task

2) Safety is another constraint which is always allied with RL (Chen et al.,2020)

3) High Dimensional Modelling is again one factor which makes RL use grim in real time applications

4) Long delays in seeking the optimal reward policy leads to a time inefficient system.

5) Exploitation in explorations vs. exploitation problem can lead to stay in optimal policy so far explored.

6) Personalization of a real time system is one such point which has always remained a zone of research until now.

Despite of the challenges mentioned above (Chua et al.,2018),(Dean et al.,2019),(Dulac-Arnold et al,2019),if the Reinforcement Learning Models are used wisely owing to it's distinct strength to connect with its environment and its sample efficacies, it may be trained for certain real world applications to perform brilliantly along with certain Bayesian Rules or Markov Decision Processes put in place as per the need.

5. Model Based vs Model Free system

Model Free (MF) RL implies that the learning without an inherent framework is possible as well.MF based RL is developed with learned framework to minimize the sample complexity. Although the sample-based efficacy is impractical for certain real time applications, therefore the acquired data set is used with the model ambiguity (Feinberg et al.,2018) for learning efficiency is a powerful technique where sophisticated learning procedure is used but for the continuous control tasks several structures such as parallelization, Bayesian method and off policy approaches are implemented.

In Model Based Learning the transition probabilities are employed without interaction with the environment, therefore it is widely used where interaction with the environment is tricky or impossible. Therefore, there is no option to speed up the learning through previously acquired data as in case of MF Learning. These frameworks make use of data acquired from the transition between the states.

In nonlinear applications, the basic problem arises with overfitting where the data is less and also high capacity models are required. The model poses an efficient learning while learning on sophisticated task is a scuffle.

Therefore, both Model Free and Model Based RL algorithms has their own strengths. As mentioned above the MF framework learn while communicating with its environment and take actions according to its state. In MB framework transition probabilities are derived from learned system and therefore the sample efficiency (Dean et al.,2019) is higher comparatively.in MF Learning the interaction between the agent and the environment are expensive and therefore Model Based Learning is preferred in such cases. In many cases hyperparameters are added along with heuristic techniques in order to minimize the problems sample complexity.

Therefore, developing a unique method which imbibes the positives of both the Model Based and Model Free approach will churn out the best of both the world.

6. Goal of RL

The first and foremost aim of RL is to determine an optimal policy, second objective is to optimizing the reward and minimizing the penalty during the learning. With polynomial grading in the dimension of operation and state spaces, an error term guarantees the performance of RL algorithms. But in robotic platforms, state-spaces are incredibly wide as they vary exponentially in the variety of state parameters and are constant. This exponential extension problem is known as the dimensionality curse. In an Off-policy technique (Pilarski et al., 2011), (Wen et al., 2019) exploratory approach that is different from the final strategy can be used during the learning procedure, regardless of the policy used. On-policy techniques gather environmental-related sample data through existing policy it is learning from. As a result, exploration should be incorporated into the strategy and the pace of policy changes is identified. Therefore, a Model Based inputs for a Model Free system is the need of the hour. Development of a prefect and smart prosthetic knee with the blend of off-policy and on-policy benefits could help in negating the negatives and would be helpful in determining the optimal policy with better reward function.

7. RL efficacy in Prosthesis

Survey of the existing work employs that there is still a need of a prosthetic knee joint for the transfemoral amputees which resembles the natural human gait with less energy consumption and are affordable and socio-economically accepted widely. It is conclusive that the designed work is inefficient or are not reachable to the amputees who still strive for a prosthetic knee which would suffice and fit all their needs. The existing techniques also lack the training and control system in place. Studying the efficiency of RL algorithms it seems that an approach with Model Based priors for Model Free Learning would be best suited for an automated smart prosthesis.

Following are the other few of the important aspects which should be there in the prosthetic knee joint:

a) Low cost
b) Availability
c) Considerate of Local climate and working conditions
d) Easily repairable
e) Technically functional and durable
f) Appropriately cosmetic and psychosocially acceptable

8. Conclusion

Thus, after doing a survey of the work done in the field of prosthetic knee joint till now and studying the benefits of Reinforcement Learning, the approach of Model Based outputs with Model Free algorithms would work as a good solution for developing a Smart Knee Joint. In further research we would be working on developing a novel approach which would be used to develop an Artificial Knee resembling a natural human gait.

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