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Estimation of Knee Joint Motor Position based on Prediction of IMU Gait Cycle in Lower Extremity Exoskeleton

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Abstract

A rehabilitation exoskeleton is a robot used for rehabilitation procedure. In order that the wearer is able to move freely and comfortably in wearing the rehabilitation exoskeleton, it is necessary to adjust the motor angle. The angle value applied to the exoskeleton must suit the users' needs, so that it can assist the rehabilitation process more rapidly. In this study, we used the neural network method to generate the angle of the servo motor and used the gait cycle phase as a reference signal to assist the knee joint. In order to verify the method, the experiment results were carried out in real-time application. The results show that the proposed method is able to provide the knee assist by generating the servo position from the proposed method in accordance with the reference signal.

Keywords: Rehabilitation robot, gait cycle, neural network, assistive position generation

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1. Introduction

A stroke or spinal cord injury robs humans from the ability to move. This is a serious problem that needs to be conquered by the sufferer, by undergoing a walking rehabilitation process. Moreover, when a human walks on dangerous areas and needs a lot of effort, such as for military purposes, their legs will be fatigued or exhausted, because they have reached the walking limitation. A solution to these problems is found in technology, which is always developing from year to year, in order to create advancements related to technology and healthcare. The technology we will mention in this paper is called the exoskeleton robot, developed to assist human in walking [1] or for training or rehabilitating those with spinal cord injuries [2,3].

Developing the assistive exoskeleton for rehabilitation purpose requires more effort and is challenging. The exoskeleton needs to be developed as comfortably as possible when the user wears it. The exoskeleton needs to understand the human walking intention and provides a proper assistive walk from the actuator to the user. There are two types of exoskeletons: upper limb and lower limb, which has been reviewed by [4,5]. As developed in [6,7], they proposed a transparency upper limb exoskeleton which is able to stop assisting the user when they able to move their arm themselves. Both of these works approach the pneumatic mechanical system in order to assist the upper limb for the rehabilitation purpose.

In order to develop the exoskeleton, user comfort is a crucial issue. It will harm the user if the exoskeleton movement overexerts the user's abilities. Therefore, the actuator on each joint needs to be controlled in accordance with the user needs. When discussing about lower limb exoskeletons, a lot of researchers have developed control strategies for the actuator aimed to give a signal for the movement of the actuator, built upon the human walking intention. As examples in [8,9,10,11,12], the dynamics equation for the lower limb exoskeleton are resolved and then PID controller is applied to deal with the feedback signal collected by the sensors. The actuators used in their work are AC servo motor [8], hydraulic [9], Maxon motor with harmonic drive [10, 11], DC motor [12], and BLDC motor [13]. Moreover, Lin, et.al [14] proposed a reduced adaptive function to approximate the coupling parameters which are generated from the lower limb exoskeleton in a simulation. Another approach from [15,16] implemented the FuzzyPID controller to control the actuator. Both

These works presented the dynamic simulation to get suitable models for the prototype of the exoskeleton. A Fuzzy-neuro control method has been applied for the controller in real-time application by adapting the EMG-based controller as a reference signal in order to produce the power-assist to the exoskeleton [17].

The adaptive sliding mode control (SMC) method based on RBF neural network that can recognize the rehabilitation training was proposed by Zhu , et.al [18]. In this work, they control the adaptive force as assistive generation. On the other hand, Phu, et.al [19] developed a novel fractional optimal SMC by modifying a Riccati-like equation and combining it with the cost function of the optimal control. However, this method is still developed by simulation. Furthermore, the path planning approach for adjusting the step length is presented in [20]. In this work, the controller mimics a kinematic constraint between the knee and hip joints during the swing phase of the gait, such that movement is not dependent on time. Different with Siddique, et.al [21], they controlled the knee joint based on the foot sensitive resistors (FSRs) and the encoder from the sagittal plane during the swing phase of the gait. Another work, [22], also implemented the gait data CGA database to make the exoskeleton realize the moving gait in the walking cycle. Another is a velocity-field based controller presented on [23] by comparing guidance and disturbance characteristics to be a potential-field based controller. In this work, they discussed various potentially beneficial characteristics of flow controller.

The assistive torque for the joint actuator made of coupled electric DC motors is presented by Pirjade, et.al [24]. The assistive torque was generated based on the walking gait cycle obtained from mimicking the video of human walking on the treadmill. An optimized compliance algorithm also needs the motion trajectory body which can be collected by using inertial and EMG sensors, where this approach was presented on [25]. The gait signal from knee joint external periodic signal also can be simulated using the central pattern generator (CPG) for controlling the exoskeleton movement based on the gait cycle generation [26]. A lightweight lower limb exoskeleton proposed on [27] only controlled the hip joint and both knee and ankle joint unpowered joints. The motors only controlled the hip joint and let the knee and ankle joint move according to the principle of torsion spring clutch which can reliably switch phase to standing phase. The control system framework introduced a controller method based on finite state machine. While Wang, et.al [28], proposed a slider-crank mechanism to handle the bending angle while the user did deep squat by using the hydraulic cylinder, the mechanism placed on hip joint exoskeleton and used the Adams to show the validity of the design. A simple adaptive control (SAC) force servo hybrid control strategy was proposed by Feng, et.al [29]. In this work, they judge the rotate velocity of hip joint and then switch the control strategy between SAC and auxiliary force servo control strategy. In contrast from work of [30], they used four stepper motors which are distributed in hip and knee joints. In this work, they used pressure sensors on the bottom of foot to facilitate the walking gait cycle recognition of different user gait cycle. While Sánchez, et.al [31], proposed a control strategy based on a custom assist-as-needed algorithm that proportionally applies torque only when the user deviated from a pre-programmed correct pattern. Chen, et.al [32], adapted the uncertain parts such as internal and external factors to the control system which is the LQR method to optimize not only the state of the lower limb system, but also the system robustness and stability. A new mechanical configuration of lower limb exoskeleton has been introduced on [33]. The control strategy in this work analyzes the human body and then adjusts the device based on the dip angle and a convenient angle length from human walking. Moreover, Susanto, et.al [34] presented the predictive Artificial Neural Network (pANN) in order to generate the assistive force for the lower limb exoskeleton. In this work, the reference signal was collected from the Center of Pressure (CoP) and walking gait cycle.

This work will focus on the actuator assistive generation for the lower limb exoskeleton on the knee joint. The walking intention is able to recognize by using the walking gait cycle presented in this work by using our previous work by using the IMU sensor on the knee joint [35]. in contrast with Sukumpee [36], they utilized the Kinect sensor for determining the knee angle correction for analysing the gait cycle during walking. As the actuator, in this work the servo motor was used for providing the assistive walking for the user. The gait cycle analysis also generated from the IMU sensor which different configuration from our previous work [37]. Due to servo motors used in this work, therefore the servo position was used to estimate the assistive signal according to the walking gait cycle from the human walking.

2. Mechanical Design

In this work, the exoskeleton will be placed at the thigh to the knee joint of the human body as presented on Fig. 1. As presented on Fig. 1. (a) and Fig. 1. (b), the thigh part was constructed to be able to stretch until

175 mm for maximum and 105mm for the knee joint. Therefore, this mechanical is suitable to be used for those who has a thigh diameter about ± 60 cm. The total length of the knee joint mechanical was 210mm and suited to a user with a height of 160-170cm. The 3D overview of the mechanical design is depicted on Fig. 1. (c), where it explains the battery slot, servo motor mounting, and belting rail designed to be placed on the user waist. To make the knee joint able to move according to the motor position, it has a connecting shaft for connecting the Bowden cable to the belting rail on the waist of the user. The real prototype of the exoskeleton presented on Fig. 1. (d) and Fig. 1. (e). On the prototype, the IMU sensor was mounted to the mechanical on the knee of the user. The IMU sensor was placed to analyze the gait cycle of human walking. The prototype also constructed by the miniPC as the main controller and two servo motor which is a DS5160 Digital baja servo.

In order to develop the motor position estimation for an assistive rehabilitation exoskeleton purposed, the system architecture was designed to fulfill this requirement. The system architecture can be seen on Fig. 2, which consists of three parts, namely signal processing, main controller, and the actuators. In the signal processing part, the IMU sensor was plugged in to the prototype of the exoskeleton on each knee joint of the user. Then, the signal conditioning will filter the noise from the angle reader and calculate it on Arduino controller board. In this work, we just used the pitch angle which is generated by the IMU sensor and collected it from the user while they are wearing and walking on the flat floor. Furthermore, the pitch angle which was collected by the system will be translate into the gait cycle of the human walking. Each walking step needs to be recognized so that the system can provide a proper angle from the servo motor. Each walking gait step will be recognized by using the Neural Network method in the main controller which is a miniPC Intel NUC. Then all of the walking gait cycle will be used for the input of motor servo position estimation. Moreover, the result of servo position estimation will send to each servo to move the angle of the servo motor according to the estimation position results through the servo controller.

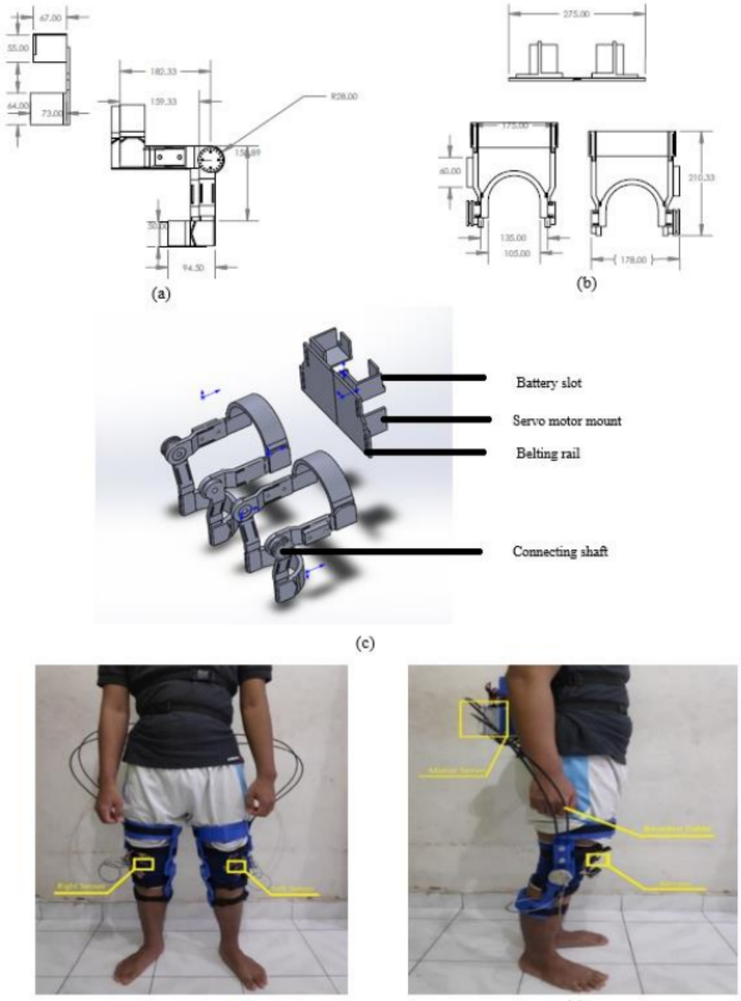


Fig. 1. The mechanical design of the knee joint lower limb exoskeleton of the (a)front view, (b)top view, (c)3D overview of knee joint design(d)prototype of the knee joint by front view, (e)prototype by side view.

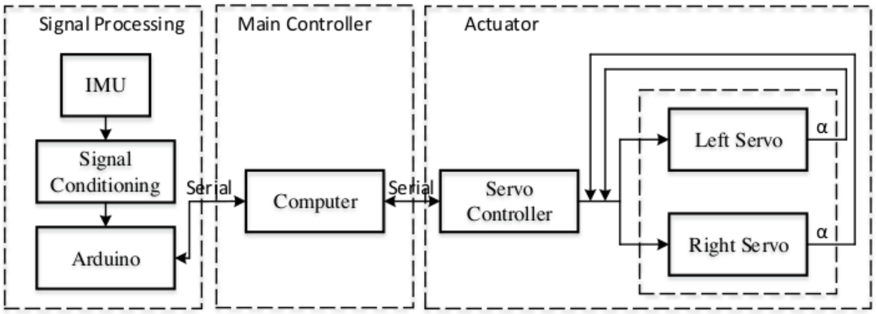


Fig. 2. System architecture of knee joint exoskeleton.

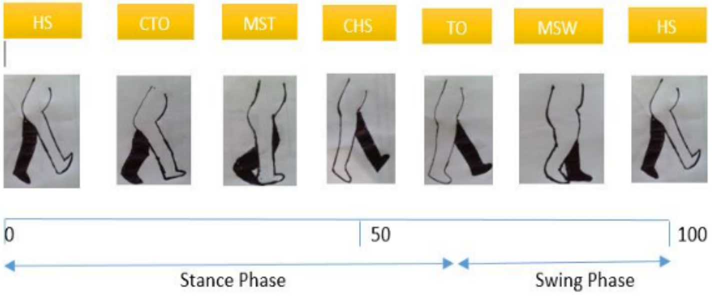


Fig. 3. Human walking gait cycle.

3. Motor Position Estimation

All calculations of the servo position are done in main controller, which is a miniPC, by using the Neural Network method. This method is also used to recognize the human walking gait cycle of each walking step. The human walking analysis was done according to the walking gait cycle depicted on Fig. 3. Fig. 3, shows six different positions of the walking step namely heel strike (HS), counter toe-off (CTO), mid stance (MST), counter heel strike (CHS), toe-off (TO), and mid swing (MSW). The IMU sensor will recognize each walking process and which foot will step or move first, and then send this data to the Arduino for the input data before generating the servo position.

The motor position generation architecture can be seen on Fig. 4. This architecture used the walking gait cycle step as the input system and consists of two hidden layer which has 5 nodes of each hidden layer. The output of this system is angle of the left and right angle (θ). Thus, angle result produced by the system according to the human walking gait activity. The output from motor position generation cannot be implemented to the servo motor yet. Therefore, we need to transform the angle result into a value which is understood by the servo motor. To transform the angle, we referred to [31], which is used the Kinect sensor to estimate the walking gait motion and provide a simple equation by implementing the geometry formula and illustration in order to get the angle. The illustration of knee angle calculation can be seen on Fig. 5.

(1)
$$\alpha = 180^\circ - \theta$$

The equation (1) describes the relation between output estimation angle and the maximum estimation motor servo angle. The θ denoted to the angle result from the estimation method and the α described the angle estimation of the servo motor for every walking phase. The angle estimation result of each walking phase presented in Table 1, where the maximum angles are presented on the swing phases i.e. MSW and MST. In order to distribute the angle estimation to servo motors, the equation (1) can be used to translate the angle

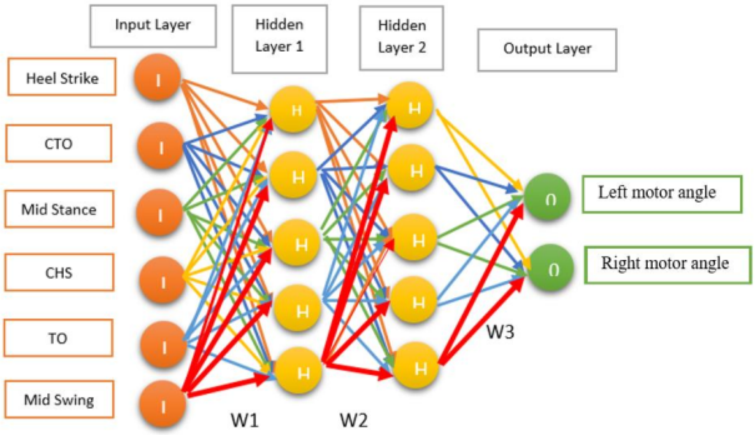


Fig. 4. The motor position generation system.

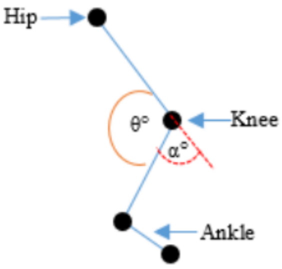


Fig. 5. Knee angle estimation position illustration.

Table 1
The knee angle estimation for each walking phase

No	Walking gait process	Left angle (θ°)	Right angle (θ°)
1	HS	0	0
2	CTO	35	0
3	MST	60	0
4	CHS	0	0
5	TO	0	35
6	MSW	0	60
7	HS	0	0

estimation from IMU sensor recognition into servo angle input. Because of this experiment was done in real-time application, then the maximum knee angle which is produced by the exoskeleton when the user stands up straight is about 150°. This angle would replace the equation (1) which is 180° into 150°. Therefore, the maximum angle estimation presented in Table 2 shows 150° for the angle estimation of 0°. While CTO and TO angle estimation in real-time is only able to produce around 20° and let the maximum angle estimation for servo around 130°. However, for MST and MSW in real-time application also produced the same angle as the estimation angle, therefore the results are as same as the calculation by using the equation (1).

Table 2
The maximum servo angle estimation for each gait cycle

No	Walking gait process	Left angle servo (α°)	Right angle servo (α°)
1	HS	150	150
2	CTO	130	150
3	MST	90	150
4	CHS	150	150
5	TO	150	130
6	MSW	150	90
7	HS	150	150


(a) (b) (c) (d) (e) (f)

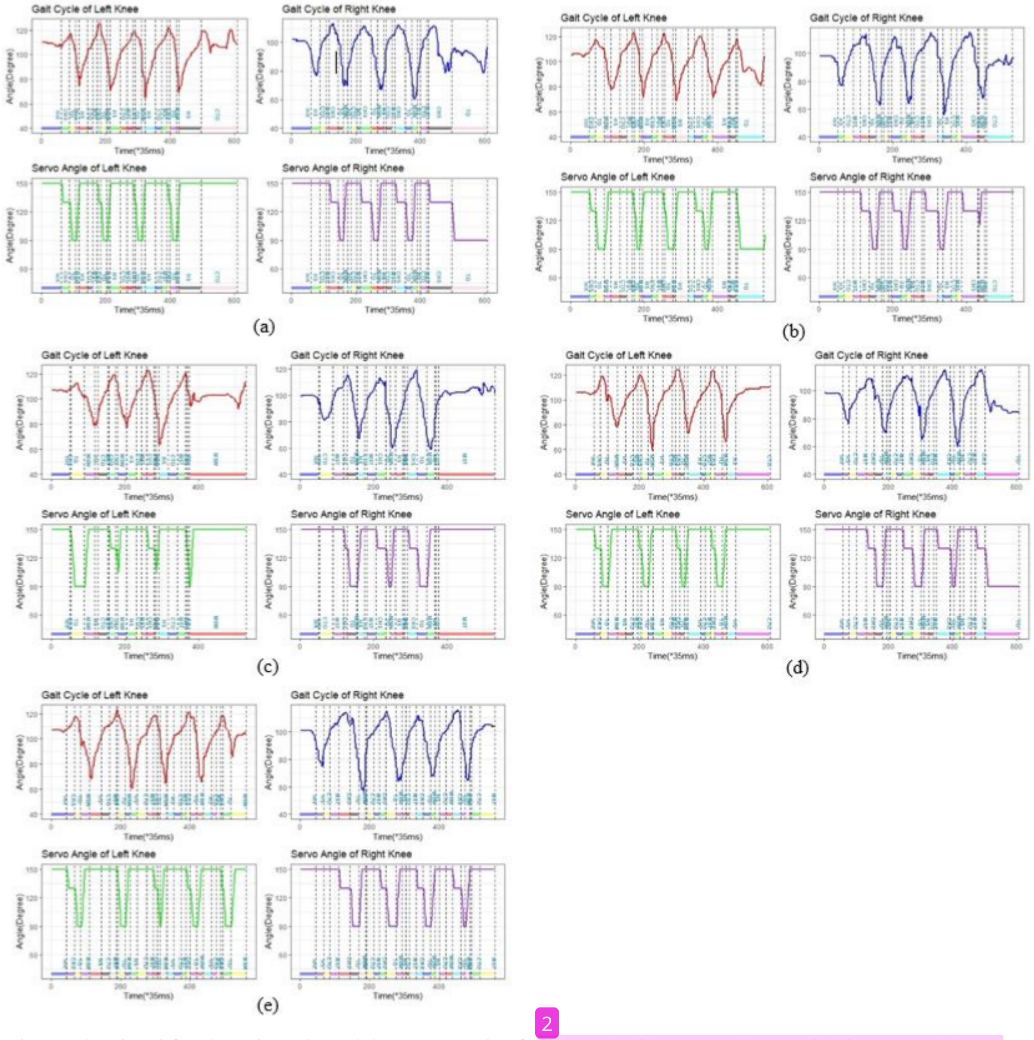
Fig. 6. The walking gait phase (a) heel strike (HS), (b) contralateral toe-off (CTO), (c) mid stance (MST), (d) contralateral heel strike (CHS), (e) toe-off (TO), (f) mid swing (MSW).

4. Discussion

To verify the performance of the proposed method, we implemented in real-time application for the lower limb of exoskeleton on knee joint. The testify performance was done by collecting five walking data on the flat floor and wearing the exoskeleton prototype while walking. For the first stage of testing out the exoskeleton prototype, we obtained five different users with different ages and heights, with 2 cycles of walking. Each of walking cycle consist of the gait phase as presented on Fig. 6. The user also used his right foot for the initial stride followed by left foot. Thanks to IMU sensors which are placed for each knee, the system is able to recognize the initial step of user walking intention. Therefore, the motor will understand which motor should be moved first as the assistive movement.

The result of first experiment described on Fig. 7.(a), where the red line denotes the gait cycle result of left knee and blue line for the right knee. The green and purple line represented the left and right knee motor position respectively. From the results on Fig. 7.(a), on the CTO phase on the right motor presented the flat signal longer than the left motor. This phenomenon will always happen because the angle results from the proposed method generated the angle signal reached the maximal angle of the motor, and also the phase angle for CTO phase on the peak of the signal. Thus, the shape of the motor signal looks like a truncated signal. The truncated signal is not only present on the first attempt but also on all of the signal results of the user. The servo angle was fed according to the maximum angle position estimation which is presented in Table 2. The first attempt of wearing the exoskeleton which is presented on Fig. 7.(a), the CTO phase of left angle reaching a maximum angle which is 90 degree, therefore the signal shape looks like trimmed. The flat signal condition depended on the length of time a user is walking and producing a walking phase and the IMU delay reading angle in certain condition.

As for the right foot on Fig. 7.(a), the first step did not show any angle increase because there is no indication of changing angle in three steps walking phase. The right foot remains straight to the ground while the user walks. Therefore, it is hard to generate the motor position because of the gait cycle as a sample train only consists of six cycles.



(a) (b) (c) (d) (e)

Fig. 7. The signal for the gait cycle and the servo angle of (a) user A, (b) user B, (c) user C, (d) user D, (e) user D, when they walked on the flat floor with normal walking speed.

While the user B on Fig. 7.(b), presented a signal which is not much different from user A. User B produced a wider signal at the first stride, indicating that the user walked with wider stride when walking and wearing the exoskeleton on the knee. And the servo position also generated a long-saturated signal at the 150° at the CTO phase for the right knee angle. Meanwhile for the user C shown on Fig. 7.(c), the estimation servo angle for the knee joint generated a position of about 110° for the TO and CTO phase for the left knee joint. This happens because the knee angle which is produced by the IMU sensor is around 80° for the TO and CTO phases, therefore it indicates that the left knee strides a bigger step than usual step.

This phenomenon will affect to generate the assistive signal from the motor in form of position. These Fig. 7.(d) and Fig. 7.(e), indicate that the user walked with wider step and slightly move faster than the other. This is denoted by the missing gait phase on these signals. Based on these experiments, it is shown that the motor was able to move according to the signal given by the IMU gait cycle recognition and understand which knee should be assistive first. However, due to the limitations of the servo motors, the signal produced for assisting the knee was not really satisfactory because it produced a flat signal when it reached the maximum position.

5. Conclusions

This work presented the development of lower extremity of the exoskeleton robot for knee joint. The IMU sensors was used to recognize each gait cycle phase which is mounted on left and right knee. In order to assist the users' knees, this prototype has two servo motors in it, and used the Neural Network method to generate the proper position for each knee. From the experiment results, the servo motors are able to produce the position in line with the gait cycle signal given by the IMU sensor. However, due to the limitation of motor position, the signal presented by the servo motor showed a flat signal when the gait phase reached the maximum angle. Therefore, in the future we will translate the servo position into torque to make the user more comfortable when wearing this exoskeleton.

Acknowledgements

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