

Design and Validation of a Knee Exoskeleton Prototype for Squatting Operations

Sofía Regalado¹, Alejandro Pereira², Sarah De Marchi¹, Angel Dacal-Nieto^{1,*}, and Erika Triviño-Tonato¹

¹CTAG—Centro Tecnológico de Automoción de Galicia, O Porriño, Spain

²Faculty of Industrial Engineering Universidade de Vigo, Vigo, Spain

Email: sofia.regalado3549@ctag.com (S.R.); apereira@uvigo.gal (A.P.); sarah.demarchi3754@ctag.com (S.D.M.); angel.dacal@ctag.com (A.D.-N.); erika.trivino@ctag.com (E.T.-T.)

*Corresponding author

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Abstract—Work-related musculoskeletal disorders affect a considerable number of workers in the manufacturing sector and is one of the main causes of sick leaves and absenteeism. The use of exoskeletons presents an alternative to reduce musculoskeletal disorders incidence rates and improve performance and human's well-being when full automation of processes are not feasible and repetitive/demand tasks must be carried out manually. Among the different body regions affected by musculoskeletal disorders, knee injuries present a high prevalence. In this work, we propose the development and evaluation of a passive exoskeleton prototype with the aim of reducing muscle activity during squatting movements. The prototype was fabricated by 3D printing methodology using an environmentally friendly material. Moreover, it fulfilled the requirements of low price, low weight, and possibility of customization. Preliminary results show a reduction of muscle activity on the leg equipped with the prototype, but further investigations are needed to discard compensation effects on the other leg.

Keywords—exoskeleton, lower limb, knee, biomechanics, design, 3D printing, manufacturing

I. INTRODUCTION

Exoskeletons are wearable devices designed to provide physical assistance and reduce muscle activity and fatigue, thus reducing the incidence rate of musculoskeletal disorders, and improving performance and human's well-being in industrial medical, and military scenarios [1–5]. These devices can be categorized as active that requires power, or as passive that uses mechanical actuators, such as springs and dampers, to provide support during movement [6]. Currently, several devices for neck [7], shoulders [8, 9], trunk [10, 11], hands [7, 12], and lower limbs [13] can be found commercially available.

In the context of industrial environments, exoskeletons have been employed to decrease the rates of Work-Related Musculoskeletal Disorders (WMSDs) [14] usually associated with typical tasks that involve the handling of heavy loads, execution of repetitive movements and adoption of awkward and nonergonomic postures. WMSDs are characterized by pain and loss of physical function in the body, which limits a person's activities and restricts their participation in the workforce. According to the definition of the European Agency for Safety and Health at Work (OSHA) [15], WMSDs cover a wide range of inflammatory and degenerative diseases including inflammation of the tendons, nerve compression and degenerative disorders occurring in the spine. The body regions with the greatest prevalence of WMSDs are the low back, neck, shoulders, knees, forearms, hands, and ankles/feet. Jin *et al.* [16] make a study focused

on lower extremity musculoskeletal disorders. It was shown a high prevalence of knee and ankle/feet injuries among 7.9 k manufacturing workers that were evaluated.

Although exoskeletons have already been recognized as a promise tool towards the establishment of more human-centered industries, their development and implementation still face several challenges [17]. Besides of being efficient in reducing muscle load, exoskeletons must also be comfortable, safe to the user and affordable for the companies to encourage their adoption.

In this work, we propose the development and evaluation of an inexpensive passive exoskeleton prototype fabricated using 3D printing techniques and a biodegradable polymer to assist knee flexion/extension movements with the aim of reducing muscle activity during a squatting task, commonly performed in industrial scenarios.

II. BACKGROUND

Currently, different knee exoskeletons can be found commercially, while others are still on prototype or research phase [18]. Some examples are described hereinafter (Table 1).

HAL® for Well-being Single Joint Type (from Cyberdyne) [19] is a lightweight (approximately 1.5 kg) non-medical device to assist flexion and extension of knees or elbows. It is made of soft and comfortable materials and fits well users' body shape. Ski~Mojo [20] is an exoskeleton specially designed to provide assistance during skiing activities. It features a mechanism based on a powerful adjustable spring that supports around 1/3 of the body weight. By compressing the springs in the bending phase, it restores energy and increases muscle power tenfold during extension. Although both devices present very interesting characteristics such as low weight, easy of donning and doffing, and fits all adult morphologies, more insights and tests would be necessary to demonstrate a full feasibility of use in industrial scenarios.

LegX (from SuitX, now owned by Ottobock) [21] is a leg support exoskeleton that provides two modes of assistance to the user while performing knee flexion/extension movements. The locking mode is beneficial for static tasks, while the spring assistance mode is beneficial for dynamic tasks where the work height varies. Research carried out simulating workplace tasks has shown that LegX could reduce muscle strain on the quadriceps while squatting. However, its implementation in industry could be constrained due to potential safety issues.

Table 1. Comparative table of knee exoskeletons

Knee Exoskeletons	Weight (Kg)	Characteristics	Application
This work	1.72	<ul style="list-style-type: none"> - Inexpensive - Comfortable - Easy to don and doff - No battery needed - Promising results on reduction of muscle activity 	Industrial
HAL® for Well-being Single Joint [19]	~1.5	<ul style="list-style-type: none"> - Comfortable - 2h battery lifetime - Able to perform assistance in alignment with the wearer's "will" 	Non-medical/ Training
Ski~Mojo [20]	-	<ul style="list-style-type: none"> - Adapts to the morphology of each person - Comfortable - Lightweight - Bear the load of 1/3 of the body weight 	Sport performance/ Skiing
LegX [21]	-	<ul style="list-style-type: none"> - Significant reduction of the muscle activity 	Industrial
Marsi Active Knee (MAK) [22]	2.80	<ul style="list-style-type: none"> - Safe and feasible - 4h battery lifetime - Promising results on device efficacy 	Medical / Gait assistance
RoboKnee (prototype) [23]	1.13	<ul style="list-style-type: none"> - Low impedance to the user - Natural interface - Simple control algorithm - Bulky - Difficult to don and doff - Short battery lifetime 	Walking assistance
Knee exoskeleton (prototype) [24]	1.07	<ul style="list-style-type: none"> - Promising results on cycling power enhancement - Improvements of structural rigidity needed. 	Sport performance/ Cycling
KEA device [25]	0.67	<ul style="list-style-type: none"> - Compact - Lightweight - Inexpensive - Significant assistance providing at least half of the total knee-extension moment - Design improvements needed. 	Rehabilitation
PPKE (prototype) [26]	0.90	<ul style="list-style-type: none"> - Energetically autonomous - Adaptable - Nimble - Effective on muscle activity reduction 	Industrial

Marsi Active Knee (MAK) [22] is a lower limb exoskeleton prototype for the knee joint with one active degree of freedom designed for gait assistance in neurological patients. The action of the device is based on the actuation of an electric motor that, in combination with the gear, provides the expected torque and speed. Although the MAK exoskeleton seemed to afford positive preliminary results with respect to its safety, feasibility, and user acceptance, the authors suggest that its efficacy should be further investigated, and more advanced improvements should be implemented to prevent unexpected device behaviors in medical context. RoboKnee is an exoskeleton prototype [23] for enhancing strength and endurance during walking. It uses a series of elastic actuators and was shown to present low impedance to the wearer and a natural interface. However, the prototype did not meet the requirements of long lifetime battery and ease in donning and doffing.

Chaichaowarat *et al.* [24] study a passive knee exoskeleton prototype for cycling assistance. This device has a mechanism based on a torsion spring that stores energy during knee flexion and releases it during extension movement. It was shown to decrease knee extensor muscle activity and the increase of knee flexor muscle activity with the torsion spring support, leading the hamstrings gradually worked out. For the proposed application (cycling assistance), this is a positive effect that would result in long-term cycling performance improvement.

Spring *et al.* [25] developed a Knee-Extension Assist

(KEA) device which was designed to help individuals with quadriceps muscle weakness to perform sit-to-stand and stand-to-sit tasks. Researchers have shown that the KEA successfully assisted the tasks by providing at least half of the total knee-extension moment required and allowing a slower and thus more controlled task completion. Future research is proposed by the authors with the aim to reduce cable-case friction and refine the locking mechanism.

A passively Powered Knee Exoskeleton (PPKE) [26] prototype was developed to provide power assistance during squat lifting of objects from the ground. The device was shown to be energetically autonomous, adaptable, and nimble thus making it suitable for the industrial use. Results have shown that PPKE effectively reduced peak muscle activity 30–40% during the first five squatting cycles. As future work, authors propose clinical testing with metabolic cost estimation to further improve the design.

It can be seen that there is still a need to keep researching in the area of knee exoskeletons for industrial applications focused on specific tasks, like, for instance, those requiring squat movements. Additionally, features such as low price, low weight, customization capabilities, and environmental respect (biodegradation and/or recyclability of materials) are not always fully supported.

III. FUNCTIONAL REQUIREMENTS AND PROTOTYPE DESIGN

Besides of offering assistance during repetitive squatting movements and reduce muscle activity of lower limb muscles, it is well known from previous experiences that an

exoskeleton must feature a series of characteristics to facilitate their implementation in industrial scenarios [1]. For instance, the device cannot impose constraints on work performance, thus it should be safe and adjust correctly to the user's body, be comfortable and lightweight, allowing an easy donning and doffing without external help and providing freedom of movement. Another potential implementation barrier in industry is the price, so an ideal prototype must be unexpensive and environmentally friendly.

Considering these requirements, in this section the design of the prototype is presented. The main components of the prototype developed in this work are shown in Fig. 1 and comprise: 1) torsion springs, 2) one hinge, and 3) thigh and leg cuffs, which were selected accordingly to fulfil the requirements needed.

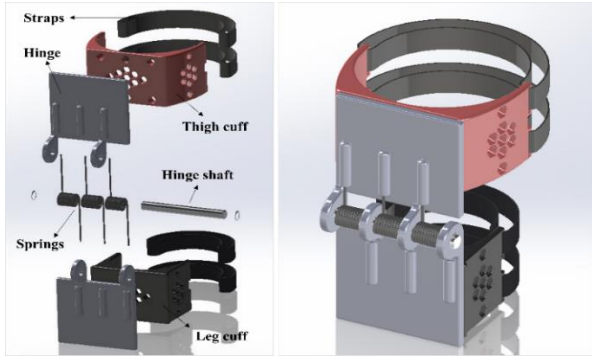


Fig. 1. Main parts of the exoskeleton prototype (left) and fully assembled device (right).

A. Torsion Spring

The torsion spring is the passive element that produces an external force and provides assistance to the muscles to perform the movement. In this work, the torsion spring was selected according to its low cost and ease of assembling to the prototype design. The number and model of the springs was determined based on the percentage of torque that the exoskeleton prototype is intended to decrease. Static analysis was carried out for calculating the torque in a 90° knee flexion position as represented schematically in Fig. 2. In this calculation, it was considered only the left side of the body, and that head and trunk are perfectly symmetric. The total mass of the limb and the length of each part was assessed through anthropometric analysis. It was assumed that the mass of hips and thigh represents 60% of the total mass of lower limbs, while the leg represents 30% and the foot 10%. The weights were calculated multiplying the mass of the body parties by the gravitational acceleration (9.8 m/s²) (Table 2).

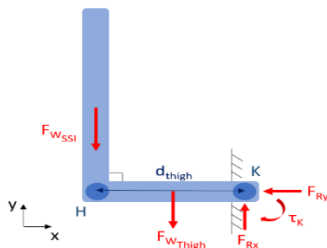


Fig. 2. Schematical representation of a 90° knee flexion. Where: knee joint (K), hip joint (H), weight of the thigh ($F_{W_{Thigh}}$), weight of the left upper limb ($F_{W_{SSI}}$), the reactive force in the X-axis (F_{Rx}) and in the Y-axis (F_{Ry}), and the torque applied on the knee joint (τ_K).

Table 2. Anthropometric analysis

Body part	Length (m)	Mass (Kg)	Weight (N)
Lower limb (left)	-	11.6	113.8
Foot (10%)	0.24	1.16	11.4
Leg (30%)	0.38	3.48	34.1
Thigh (60%)	0.45	6.96	68.3
Upper limb (left)	0.69	21.1	207

In the static analysis, according to Newton's laws, the forces and torque involved in the system are balanced, i.e., equal to zero Eq. (1). The limbs are kept in a fixed position. Torque can be used to determine the amount of stress placed on the joint and is calculated by multiplying the force applied and the distance from the axis of rotation, in this case the knee joint denoted as K in Fig. 1, to the point where the force is applied Eq. (2). On the other hand, there are two different types of forces: the reactive forces that act on the knee joint in response to external loads and the weight of each body part.

$$\sum F_x = 0; \sum F_y = \sum \tau = 0 \quad (1)$$

$$\tau_i = F_i \times d_i \times \sin \theta \quad (2)$$

where τ is the torque, F is the force (reactive force or weight), d is the distance between the knee joint and the force, θ is the angle formed by the axis of rotation of the knee joint and the force applied. The angle θ is set to 90° knee flexion while it is the maximum torque that could be applied since $\sin(90) = 1$. The necessary torque is calculated to counteract the existing one and keep the knee static.

The calculations show that a torque of 107.3 Nm is required to maintain the knee in a fixed position. The commercially available spring T135-180-735-L (ASRaymond™) has a torque of 4.52 Nm. Therefore, 3 springs had to be sequentially assembled on the prototype to provide a total torque of 13.56 Nm with the objective to achieve a maximum of 13% reduction of the momentum applied on the knee when performing the movement.

B. Hinge

The hinge is the mechanism that allows the rotation of two parts connected by the axis where the springs will be placed. The force generated by the spring is transferred to the hinge and generates movement. A door-style hinge was selected due to its simplicity. This element comprises two leaves that fold around an axis. The dimensions of each leaf were thought to accommodate the three springs and that it could be involved by the fabrics utilized to assembly all the prototype parts while keeping its axis aligned with the knee axis. Each leaf counts with three channels in one face where the springs are inserted, and with two holes in the back to accommodate a metallic shaft located in a such way that once the hinge is assembled, the load is distributed more efficiently. The diameter of the holes was selected considering the diameter of the spring. Once assembled, the maximum opening angle of the hinge is 180° without tensioning the springs.

C. Thigh and Leg Cuffs

These elements have a semicircular geometry in the inner face to adapt to the lower limb shape, and flat at the outer face. To better adapt to the user body, the thigh cuff featured lateral curvatures in the outer face and had bigger dimensions than leg cuff. The inner wall is covered with a hypoallergenic

foam to provide comfort to the user. Both have lateral openings to accommodate the fastening bands. These elements are also covered with a resistant fabric designed to keep the hinge aligned, avoiding the use of rivets, bolts, and clamps, and simplifying the overall device assembly.

IV. PROTOTYPE FABRICATION

The first step of prototype fabrication was its design using Computational Assisted Design (CAD) software SolidWorks 2021. The load simulation was not executed due to technical challenges and computer instability during the attempt. A computer with advanced specifications is expected to yield accurate load simulation. Next, the main components (cuffs, hinge and joint) were created using 3D printing technique [27]. This method consists in constructing, layer by layer, a three-dimensional object from a digital model. It arises as an interesting option due to its high versatility, which allows the use of different materials, such as metals and polymers, its high prototyping speed, and especially the possibility of customization to the user. Fused Deposition Modeling (FDM) or extrusion filament material, according ISO/ASTM 52900 [28] is the most popular 3D technology where polymeric materials are extruded through a nozzle and joined together to create the desired object [29]. The springs and other small materials (metallic rings and shaft, fastening bands and fabrics) were bought from a commercial provider.

Polymeric materials allow for the achievement of resistant and lightweight products with outstanding properties. Polylactic Acid (PLA) is a non-toxic, bio-based industrial thermoplastic 100% bio-degradable that presents comparable performance to petroleum-based plastics. Because of its good mechanical properties, processability, renewability, and non-toxicity, PLA is considered today as one of the most commercially promising bioplastics. When compared with other biodegradable polymers, PLA has better durability, transparency, and mechanical strength [30]. These characteristics make PLA a suitable and environmentally friendly option in exoskeleton development.

The CAD models were imported to the slicer software (Idea maker[®] and Ultimaker Cura[®]) [31] and the parameters were set up according to the 3D printer model and fabrication requirements, aiming to reduce the time of impression and amount of material, so that we can reduce the prototype overall costs, without losing quality. The parameters used in the fabrication of the hinge, thigh and leg cuffs are shown in Table 3.

Table 3. 3D printing parameters

	Prototype component		
	Hinge	Thigh cuff	Leg cuff
Printer model	Raise3D Pro2	Raise3D Pro2	Ultimaker 3
Printer software	ideaMaker	ideaMaker	Ultimaker Cura
Material	PLA+	PLA+	PLA
Layer thickness (mm)	0.2	0.32	0.20
Temperature melting (°C)	205	205	205
Temperature bed (°C)	60	60	60
Infill density (%)	20	15	15
Infill pattern	gyroid	gyroid	gyroid
Printing speed (mm/s)	50	50	70
Type of adhesion	Skirt	Skirt	Skirt

The cost of the pieces fabricated by 3D printing technology was 23.36 €, while the other components (springs, metallic shaft and rings, fastening straps, and fabrics) costed

60.33 €, yielding a total cost of 83.69 € per prototype. The total mass of the assembled exoskeleton prototype was 1.72 kg.

V. EVALUATION OF THE PROTOTYPE

A. Use Case Simulation

Despite ergonomic advances and management, squatting operations are still present in manufacturing. In some limited cases, it may be necessary to assemble a component, work on a part, or picking a load, at a height lower than the operator's hips, with no available device or help to adjust it to the operator's hands.

In this line, a screwing operation, consisting in screwing 4 bolts at 30 cm of height with respect to the ground, has been simulated in a preindustrial scenario at the Booster Manufacturing Lab at CTAG facilities. The tests were carried out in a sensorized, modular, and adjustable testbed that simulate the end user's working environment called InteX, developed and exploited by CTAG.

B. Evaluation Protocol

Due to the preliminary nature of the prototype, the tests were performed with only 1 volunteer that was previously informed about the content of the study and signed a participation consent.

The task consisted in screwing 4 bolts in a wooden board in order to fix it to a metallic wall. Each work cycle took 1 min to be completed and was repeated 3 times (3 cycles), first wearing the exoskeleton prototype on the left leg (Fig. 3(A)–(C)) and then without wearing it (Fig. 3(D)–(F)).



Fig. 3. Snapshots of the use case performed at a simulated industrial scenario ((A)–(C), top) wearing and ((D)–(F), bottom) not wearing the exoskeleton prototype.

C. Evaluation Methods and Devices

Before the beginning of data acquisition, the participant had time to get familiar with the device and was asked to perform squat movements during 10 s wearing it on the left leg. Next, the simulated task was executed, and Electromyography (EMG) signals were measured using the sensorized shorts MShorts3 and M-Cell3 devices (Myontec

Ltd, Finland). This less invasive and wearable device measures muscle activity (surface EMG) from hamstrings, quadriceps, and glutes, it is easy to use under working clothes and fits all adults. EMG signals were collected at 1000 Hz, band-pass filtered at 40 Hz–200 Hz and then rectified and averaged at intervals of 25 samples/sec (25 Hz). Muscle Monitor software (Myontec Ltd, Finland) was used to monitor the rectified EMG signals at 25 Hz in real time and export data.

VI. RESULTS AND DISCUSSION

During the familiarization period the participant reported problems of mobility that were associated with the large gap between the hinge and the knee, which impeded the movement. This issue was solved by utilizing elastic bands to decrease this gap, thus achieving properly flexion-extension of the knee. Muscle activity data from hamstrings, quadriceps, and glutes obtained during the task execution with and without wearing the exoskeleton prototype were analyzed and compared.

Table 4 displays the mean values of muscle activity obtained during the 3 work cycles for each muscle. The percentages of reduction or increase in muscle activity were calculated by dividing the difference (z) between the values of muscle activity obtained with and without the exoskeleton and multiplying it by 100. As shown in Fig. 4, using the exoskeleton prototype in the left leg to perform the task led to a decreased of muscle activity of quadriceps, hamstrings, and glutes of this leg. Muscle activity of quadriceps and hamstrings of right leg were increased, while muscle activity of right-side glutes was decreased.

Table 4. Muscle activity of left and right quadriceps, hamstrings and glutes muscles during the task performed with or without using the exoskeleton

	Muscle activity (μV)				z	Reduction (-) / Increase (+) of muscle activity
	Without exoskeleton		With exoskeleton			
	Mean	SD	Mean	SD		
Quadriceps-L	12.7	1.6	11.6	0.6	-1.1	-9%
Quadriceps-R	13.9	1.6	18.4	1.2	4.5	+33%
Hamstrings-L	18.5	0.4	17.7	0.7	-0.8	-4%
Hamstrings-R	22.4	4.3	24.7	3.9	2.4	+11%
Glutes-L	5.4	0.5	3.4	1.0	-2.0	-36%
Glutes-R	3.8	0.7	3.0	0.9	-0.8	-21%
Left leg	36.6	1.8	32.7	1.1	-3.9	-11%
Right leg	40.0	6.3	46.1	5.0	6.1	+15%
Global	76.6	7.2	78.8	5.5	2.2	+3%

The distribution of muscle load between right and left legs was determined by dividing the sum of muscle activity exerted by one leg by the sum of muscle activity exerted by both legs (global), and then multiplying it by 100. Without wearing the exoskeleton prototype, muscle load was distributed 48 % on the left leg, while 52% on the right leg. Similarly, when wearing the exoskeleton prototype the distribution of muscle load was 42% and 58% on the left and right leg, respectively. The results show that in both cases (with and without wearing the prototype) the muscle load is distributed mostly on the right leg. However, when wearing the prototype this unbalancing was slightly higher, indicating a possible compensation on the right leg as a consequence of wearing the prototype.

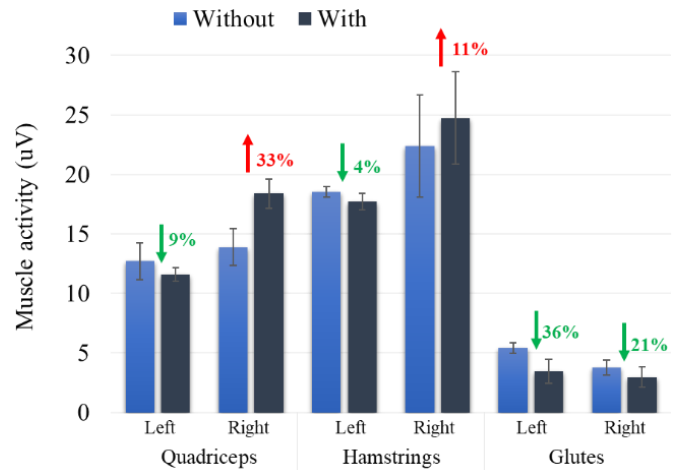


Fig. 4. Left and right muscle activity of quadriceps, hamstrings, and glutes during task executed without (light blue) and with (dark blue) the exoskeleton prototype. Note: Down arrows followed by the number denote the percentage of muscle activity reduction, while upward arrows plus a number denote the percentage of muscle activity increase.

VII. CONCLUSIONS AND FUTURE WORK

A passive knee exoskeleton prototype was designed and fabricated using a biodegradable polymer PLA through 3D printing technology. The prototype was inexpensive, lightweight, comfortable, easy to don and doff, and adjusted to the user body size, indicating that it is customizable and could be suitable for any people height and weight. In addition, it was not observed any safety issues. Preliminary tests for assessing its capability in reducing muscle activity was carried out in laboratory simulating an industrial scenario. The results indicated an overall reduction of muscle activity of the left leg when wearing the prototype. However, the present study presents several limitations and further investigation is needed, for instance, to discard the possibility that the reduction is due to a compensation on the right leg.

As future work, for a more accurate evaluation of the prototype assistance, it is proposed (i) increasing the number of participants and the familiarization period, (ii) including other assessment metrics to the protocol, such as heart rate variability to study fatigue and subjective questionnaires to determine users' acceptance, and (iii) using an exoskeleton prototype also on the right leg to obtain more accurate and statistically representative data. Regarding the prototype design, based on the preliminary results obtained in this work, several measures are proposed to obtain an improved prototype version. These improvements include (i) decreasing the gap between the knee and the springs by eliminating the hinge and fixing the springs directly in the thigh and leg cuffs, (ii) decreasing the overall weight of the device and (iii) including an anchoring system to prevent the exoskeleton to slip down the leg.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

ADN and AP conceived the idea and supervised the project; SR and ETT conducted the research and analyzed the data; SDM wrote the paper with input from SR and ADN; all authors had approved the final version.

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