Design and Pilot Evaluation of a Prototype Sensorized Trunk Exoskeleton

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***Abstract*— Trunk exoskeletons are wearable devices that support wearers during physically demanding tasks by reducing biomechanical loads and increasing stability. In this paper, we present a prototype sensorized passive trunk exoskeleton, which includes five motion processing units (3-axis accelerometers and gyroscopes with onboard digital processing), four one-axis flex sensors along the exoskeletal spinal column, and two one-axis force sensors for measuring the interaction force between the wearer and exoskeleton. A pilot evaluation of the exoskeleton was conducted with two wearers, who performed multiple everyday tasks (sitting on a chair and standing up, walking in a straight line, picking up a box with a straight back, picking up a box with a bent back, bending forward while standing, bending laterally while standing) while wearing the exoskeleton. Illustrative examples of the results are presented as graphs. Finally, potential applications of the sensorized exoskeleton as the basis for a semi-active exoskeleton design or for audio/haptic feedback to guide the wearer are discussed.**

***Clinical Relevance*— Trunk exoskeletons have the potential to reduce the risk of back injury and chronic low back pain. The sensorized exoskeleton can serve as the basis for semi-active designs that bridge the current gap between fully passive and fully active devices.**

I. Introduction

Trunk exoskeletons are an emerging class of wearable devices that physically support the human trunk, reducing biomechanical loads and increasing stability [1]. Most such exoskeletons are intended to support workers in physically demanding occupations such as warehouse work and baggage handling [2]–[4]; in these applications, they could reduce the risk of back injury associated with repetitive lifting [5], [6]. Alternatively, some trunk exoskeletons have also been proposed for use with people who already have chronic back injuries, potentially alleviating chronic pain and reducing the risk of further injury [7], [8]. In both cases, the overall goal is to reduce the prevalence of low back pain, which is a leading cause of disability worldwide [9].

Trunk exoskeletons can be broadly divided into active and passive devices. Passive devices do not contain any motors and simply support the wearer using mechanical structures [2], [4], [7], [8], [10]. Conversely, active exoskeletons include motors that can apply torques to the limbs, augmenting the wearer's movements [3], [11]–[13]. While active exoskeletons can provide more assistance than passive ones, they are also heavier, more expensive, and more complex; thus, passive exoskeletons are currently more popular [1].

As a middle ground between passive and active devices, both our research group [7] and others [10], [14] have previously proposed the development of "semi-active" trunk exoskeletons: devices that do not have large motors that could provide assistive torques, but do have sensors and smaller actuators that could, e.g., lock and unlock different joints of the exoskeleton or change the compression forces applied to the trunk. For example, our previous study [7] found that changing the amount of trunk compression makes a trunk exoskeleton more supportive for some activities and less supportive for others. Thus, dynamically detecting the wearer's current activity and adapting the exoskeleton's mechanical properties accordingly could potentially make semi-active exoskeletons provide more support than passive ones at a fraction of the power and weight required by active exoskeletons.

In the current study, we present our prototype sensorized passive exoskeleton, which includes three sensor types: flex sensors, inertial sensors, and interaction force sensors. The sensor system was preliminarily evaluated with two subjects. In the future, it may serve as the basis for a semi-active exoskeleton design and/or for audio or haptic feedback to guide the wearer during different activities.

II. Materials and Methods

A. Hardware and Software

The passive trunk exoskeleton used as the basis for this work was originally developed by Livity Technologies (Highlands Ranch, USA) and included manually adjustable trunk compression and manually adjustable stiffness but no sensors; its short-term effects on the wearer were evaluated in our previous study [7]. Full details about its mechanical design are provided in our previous paper [7], but to summarize: it is an exoskeletal thoracic-lumbar-sacral orthosis that weighs approximately 2.5 kg. It consists of multiple sections: an exoskeletal spinal column, trunk-grasping end-effectors, thoracic and abdominal front modules, and elastic straps that connect the front modules to the end- effectors. The spinal column incorporates seven variable-segment axial resistance couplings whose stiffnesses can be independently adjusted, and the elastic straps that connect the front modules and trunk-grasping end-effectors can also be manually adjusted.

In the current work, the exoskeleton was expanded with the following components:

- An Arduino Uno Rev.2 Wi-Fi printed circuit board (PCB) with an ATmega4809 microcontroller, Wi-Fi transmitter, a LSM6DS3TR inertial measurement unit (which combines a 3-axis gyroscope and a 3-axis accelerometer),

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11 input connectors, and a 12-volt battery. The PCB was placed on the back of the exoskeleton (Fig. 1).

- Four MPU6050 (TDK Invensense, San Jose, USA) motion processing units (MPUs), which combine a 3-axis gyroscope, a 3-axis accelerometer, and an onboard digital motion processor on the same silicon die. Each MPU has a size of 14x21. The accelerometers were set to a range of ±2 g and sensitivity scale factor of 16384 LSB/g while the gyroscopes were set to a range of ±250 degrees/second and sensitivity scale factor of 131 LSB / degree/second (LSB = least significant bit). The MPUs were placed on the trunk-grasping end effectors on the shoulders (Figs. 2 and 3) and lower back (Fig. 1). All MPUs were oriented so that, when the wearer is standing upright, the MPU's local x-axis points upward, the local y-axis points to the wearer's left, and the local z-axis points behind the wearer. This is also indicated in Fig. 1.
- Four one-axis bidirectional capacitive soft flex sensors (Bend Labs, Salt Lake City, USA). Each sensor has a size of 100 x 7.62 x 1.27 mm, a sensitivity of 0.016 degree LSB, and a repeatability of 0.18 degrees. The flex sensors were placed on the inside of the exoskeletal spinal column at different heights (Fig. 3).
- Two SingleTact 8 mm 100 N capacitive force sensors (Medical Tactile, Inc., Hawthorne; USA) that measure the applied force with a full scale range of 100 N, minimal detectable force of 2 g and resolution of 0.2 N. Each sensor has a size of 58 x 3.5 mm. One sensor was placed on the inside of the thoracic front module (between the wearer and exoskeleton – Fig. 2) while the other was placed at the top of the exoskeletal spinal column (Figs. 1 and 3).

All individual sensors were placed inside specially 3D printed rigid "pockets" attached to the exoskeleton, allowing easy removal for maintenance. The sensors were connected to the PCB with wires, and the collected data were transmitted using the WiFi transmitter and UDP protocol at a frequency of 100 Hz to a data collection computer, where they were received in MATLAB Simulink (Mathworks, Natick, USA).

B. Evaluation Protocol

The pilot evaluation protocol was approved by the University of Wyoming Institutional Review Board (protocol #20200129DN02643. Two participants were recruited: one woman (33 years old, 169 cm, 70 kg) and one man (23 years old, 183 cm, 79 kg). Both signed an informed consent form after having the purpose and procedure of the experiment explained to them. They then donned the sensorized exoskeleton and performed multiple everyday activities:
- Sit on a chair and stand up again,
- Walk in a straight line across the lab, turn around, and walk back,
- Pick up a light box from the floor with a straight back (i.e., squatting),
- Pick up the same box from the floor with a bent back (i.e., stooping),
- Bend forward, hold the position briefly, then straighten up.
- Bend laterally to the left, straighten up, then bend to the right.

All activities were performed starting from and ending in a straight standing position with the arms to the side. Both squatting and stooping lifts were included since stooping lifts are less ergonomic than squatting lifts and may require different exoskeleton assistance or audio feedback to remind the participant not to lift with their back [15].

Due to the pilot nature of the evaluation, no statistical analysis was done. Collected data were filtered with a Butterworth 10-Hz third-order lowpass filter, and examples of the data were manually selected for visualization.

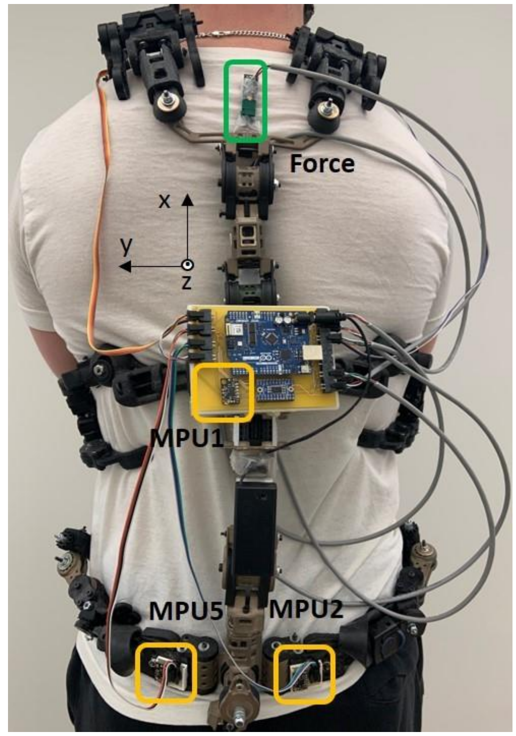

Figure 1. The trunk exoskeleton worn by a person, back view. Motion processing units (MPUs) and back force sensor are highlighted. The xyz coordinate system represents the local coordinate system of all MPUs.

Figure 2. The trunk exoskeleton worn by a person, front view. Motion processing units (MPUs) and force sensor are highlighted.

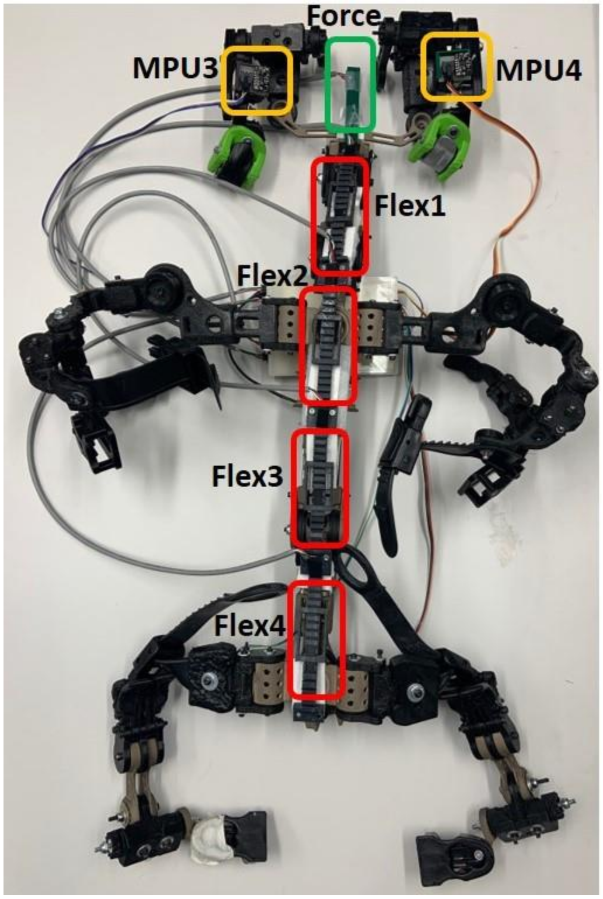

Figure 3. Inside view of the trunk exoskeleton. The back force sensor, shoulder motion processing units (MPUs) and four flex sensors along the inside of the spinal column are highlighted.

III. Results

Figs. 4-7 show examples of data during different activities:

- Fig. 4 shows a participant's MPU on the left hip (with accelerometer and gyroscope separately) as well as all four flex sensors during a squatting lift as well as a stooping lift.
- Fig. 5 shows the same MPU and the top two flex sensors during a lateral bend movement, first to the left and then to the right.
- Fig. 6 shows the MPU on the mid-back (with accelerometer and gyroscope separately) as well as the top and bottom flex sensors while the participant sits down and stands up again.
- Fig 7. shows only the accelerometer on the right hip during walking, illustrating individual steps.

The measured signals were very similar for both participants, and only one participant is thus shown per figure. Due to an error in the data collection algorithms, data from the force sensors were not yet available at time of submission and are thus not presented.

IV. Discussion

A. Data Interpretation

Results of the pilot evaluation show that the sensors exhibit intuitive, valid patterns during typical motions. For example, the flex sensors along the exoskeletal spinal column show less bending during a squat lift (Fig. 4, left), when the back should be straight, than during a stoop lift (Fig. 4, right). The accelerometer and gyroscope on the left hip also exhibit

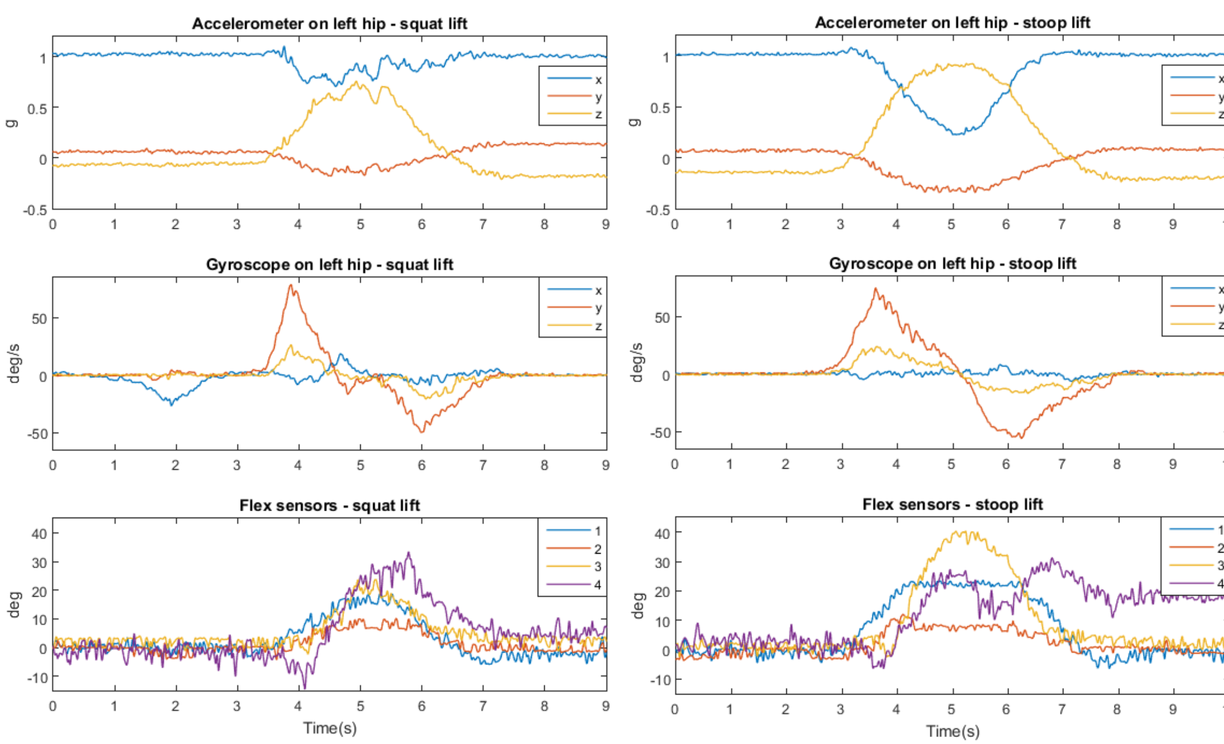

Figure 4. Examples of sensor readings when the participant is performing either a squatting lift (left) or a stooping lift (right). The four flex sensors are labeled 1-4 from the top to the bottom of the spinal column. The accelerometer and gyroscope's local coordinate system is set so that x points upward (toward the participant's head), y points to the participant's left, and z points behind the participant.

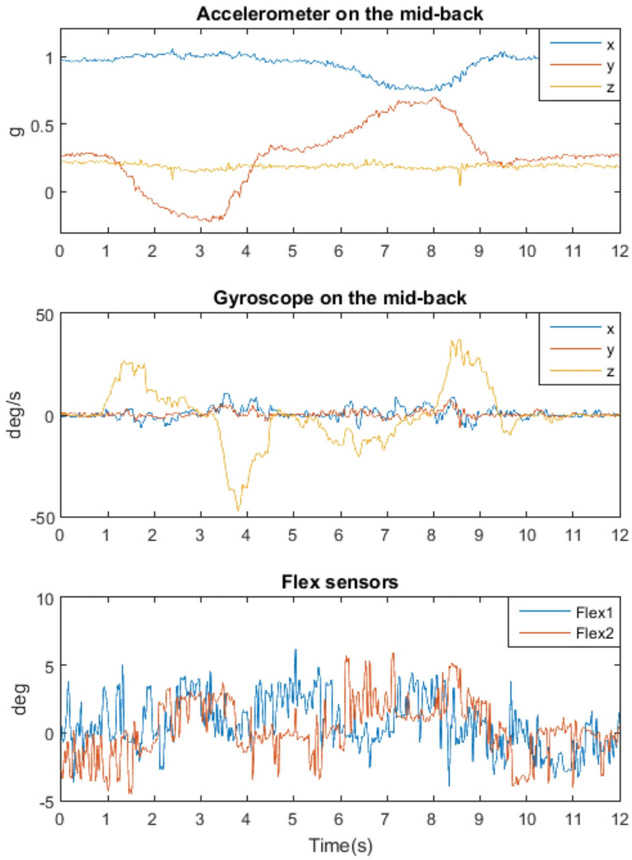

Figure 5. Examples of sensor readings when the participant first bends laterally to the left and then to the right. Flex1 and Flex2 are the top two flex sensors (on the upper back).

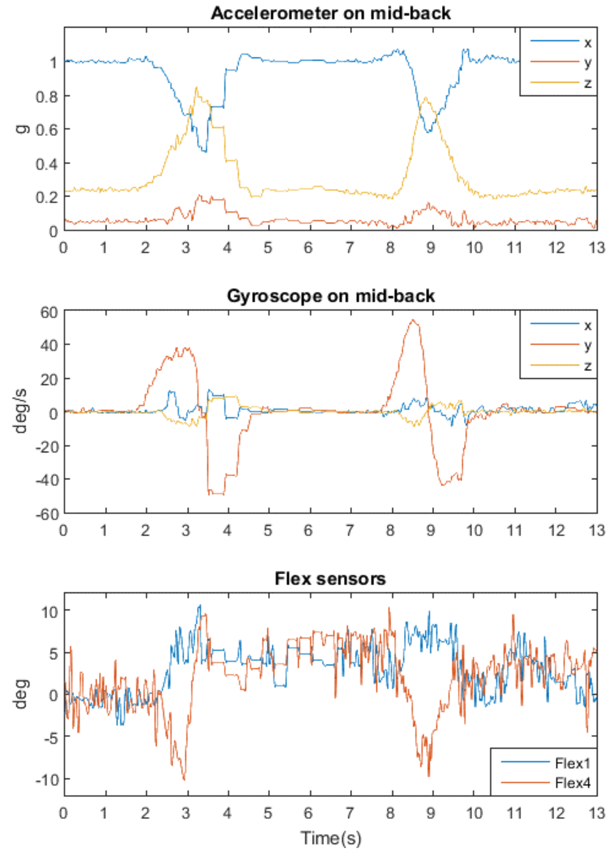

Figure 6. Examples of sensor readings when the participant stands up and sits down again. Flex1 is the top flex sensor (upper back) while Flex4 is the bottom flex sensor (lower back).

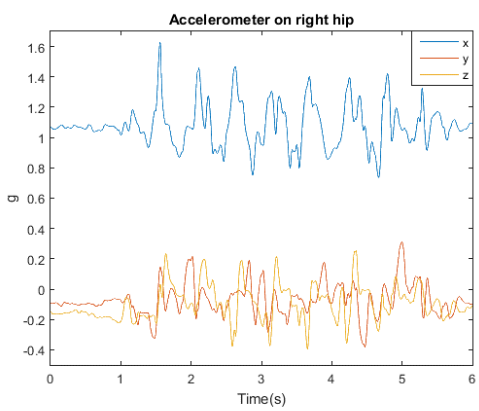

Figure 7. Example sensor reading from the accelerometer on the right hip as the participant walks, with individual steps visible on the local x-axis (global up/down direction).

differences between the squat and stoop. When stooping, participants bend forward more, resulting in more angular velocity around the gyroscope's local y-axis (i.e., more hip flexion) and more acceleration in the accelerometer's local z-axis (i.e., more acceleration forward for the participant). While no automated pattern recognition was attempted, this does indicate that the sensors in the exoskeleton would be able to differentiate between a squat lift and a stoop lift, which would assist with determining lift ergonomics and choosing an appropriate assistive strategy for the exoskeleton [15].

During the lateral bend (Fig. 5), the gyroscope shows a clear pattern of angular velocity first in the positive direction as the participant bends left, then in the negative direction as the participant straightens again; the opposite pattern is observed when bending right (which was slower in this case). The accelerometer also exhibits a clear pattern of displacement in both directions, as expected. On the flex sensors, no change was expected or observed since the 1-axis sensors are mounted so that they only measure bending in the sagittal plane.

During the stand-to-sit-to-stand movement (Fig. 6), the sensors all show a pattern of two 'events' associated with first sitting down and then standing up. It is at first surprising that the "sit" and "stand" events appear largely identical. For example, we would intuitively expect acceleration to show an acceleration of more than 1 g in the x-axis as the participant sits down. However, the movement was done slowly (taking 2 s to sit down), and there was thus relatively little acceleration due to the upward/downward movement. Instead, the change in acceleration readings is mostly due to the gravity vector turning with regard to the local coordinate system as the participant bends, moves forward and then straightens. This bend-forward-straighten process is the same for both sitting down and standing, resulting in largely identical events.

Finally, during walking (Fig. 7), the accelerometer exhibits a clear pattern of peaks associated with individual steps, which could serve as the basis for, e.g., gait segmentation.

B. *General Comments on the Sensors*

Attaching the MPU and flex sensors to the exoskeleton itself provides a more convenient alternative to donning the exoskeleton and separately placing wearable sensors (e.g., inertial sensors) on the participant. While the exoskeleton is not guaranteed to be rigidly attached to the human (which may result in some inaccuracy), the sensors are rigidly attached to the device and the wearer thus only needs to attach one item.

The MPUs and flex sensors can be considered somewhat complementary. Flex sensors only provide 1-axis measurements, but measure absolute angles. MPUs, on the other hand, provide 3-axis measurements, but absolute positions and orientations can only be obtained through integration of acceleration and angular velocity, which requires methods such as Kalman filtering and is prone to drift. When using an exoskeleton to support and monitor repetitive lifting (the most common trunk exoskeleton application [1]–[4]), the flex sensors could thus serve as the primary indicator of a lift while the MPUs could be used to, determine whether the wearer is also turning left and right to pick up and set down an object. Data from the flex sensors could potentially even be used in sensor fusion algorithms as an absolute reference for the MPUs, reducing the effects of noise on those sensors.

While data from the force sensors were not available at time of submission due to a software error, these sensors could provide additional useful information. For example, they may serve as an indicator of participant comfort, as done with standalone pressure sensors by another research group [3].

Finally, we acknowledge that, while the evaluated sensors showed promising results, the wiring used to connect individual sensors to the PCB was bulky and suboptimal. Thus, in the next iteration of the sensorized exoskeleton, we will explore either a more unobtrusive wiring setup or wireless connections between different parts of the device.

C. *Applications of Onboard Sensor System*

Since the sensors exhibit different response patterns to different activities, they could be used to automatically recognize the activity the wearer is performing, as is done with human- and device-mounted sensors in many wearable robots [16]. Our main planned application of such automated activity recognition would be a semi-active exoskeleton design. Our device already has manually adjustable trunk compression and exoskeletal spinal column stiffness, and we plan to add small actuators in the future to automatically adjust the compression and stiffness – for example, increase them to stabilize the wearer in case of perturbations and then decrease them to give the wearer more flexibility and comfort when support is not needed [7]. A similar activity recognition and adaptation approach could be used with the current sensors and assistive motors mounted on the limbs (for example, to choose the most appropriate motor control strategy for the current activity), though this is not the goal of our research group specifically.

In the absence of motors, it would also be possible to have the exoskeleton passively support the wearer and provide audio or haptic feedback during activities. For example, if the exoskeleton's sensors detect that the wearer is lifting with the back rather than the legs, the exoskeleton could emit a warning sound to remind the wearer to change their behavior. Sensor data could also be collected over a longer period of time and presented to the wearer, allowing them to determine, e.g., when it may be beneficial to manually adjust exoskeleton compression and stiffness to maximize its assistive effects.

V. Conclusion

Our pilot evaluation showed that the MPUs and flex sensors mounted on the trunk exoskeleton exhibit output patterns characteristic of different activities. In the future, the sensor system will be used as a basis for a semi-active trunk exoskeleton, for audio or haptic feedback, or for longer-term monitoring. This could, in the long-term, increase the effectiveness of trunk exoskeletons and reduce the global burden of low back pain. Additionally, the sensor system design could be adapted for use with other wearable devices.

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