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Positive Effect Study of a Passive Waist-Assistive Exoskeleton on Human Muscle Activity and Stability

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Abstract— **Investigating effects of waist-assistive exoskeleton on human muscle activity and stability can not only help human to carry heavy objects easier and safer, but also promote the development of wearable robotic devices. To this end, this paper dedicates to studying positive impacts of a passive waist-assistive exoskeleton on human muscle activation and movement stability via experimental technology under carrying task. During the experiment studying, four subjects are recruited to carry different objects under three different tasks. The experimental results show that muscle activations of the left and right thorax thoracic erector spinaes of each subject are generally reduced around 10%. Also, the experimental results confirm that the root mean square (RMS) of the center of pressure (COP) of each subject is averagely reduced about 8% and movement trend of each subject's trunk has become smoother and more stable.**

I. Introduction

Carrying object is a common human daily behavior, which needs human to bend over and may cause the low back of human to be painful. In order to prevent low back pain attack and make human carrying behavior easier, more and more researchers from the community of robotic have been dedicated themselves to developing different exoskeletons to release human from the manual handling work [1].

Due to the portability and practicality of passive exoskeletons, researchers have designed, tested and confirmed the effectiveness of different passive exoskeletons. Early in 2007, Naito et al. [2] have designed a wearable autonomous and lightweight exoskeleton to reduce muscular fatigue of carpentry workers. Their results show that the robot reduces the muscular fatigue of carpentry worker by providing suitable assistive force. In order to reduce the shoulder physical strain as well as global physiological strain of carriers, Maurice et al. [3] presented a thorough in-lab assessment of a novel passive exoskeleton called PAEXO. This experiment can assist without degrading balance. Aiming at reducing the average absolute joint torques, the exotendon concept in a lightweight exoskeleton was implemented by Wietse et al [4]. The support given by the exotendon is up to 35%.

Reviewing the currently-existing studies, it could be found that most of these terrific works either focus on verifying effectiveness via comparing the surface Electromyography (sEMG) signals, or muscle metabolic costs. For examples, Wei et al. [5] accessed the passive exoskeleton mainly by comparing muscle activation and metabolic energy cost with the situation without exoskeleton. They found that lower muscle activity (by 35%~61%) and lower metabolic cost of energy (by 22%) are required when wearing the exoskeleton. Andrej et al [6] investigated the effect of a performance augmenting exoskeleton on the metabolic cost of an able-bodied user/pilot during periodic squatting and results had shown a great promise for the robotic exoskeletons. Jeffrey et al [7] confirmed the use of an EXO prototype changes both the individual's limits of stability and postural sway.

Few studies concentrate on investigating the balance or stability impacts that the exoskeleton imposes on the users under carrying task.

To this end, the purpose of this paper is to validate the effectiveness of the presented exoskeleton by experimental methods of sEMG, COP and kinematic indexes. This paper studies the situation of carrying three different weights under three different tasks in order that we can compare the differences in many aspects. To achieve this goal, we choose three representative tasks and each of these is divided into two or four phases depending on the bending angel and corresponding task. After that, RMS values of muscle activation and kinematic indexes of each phase are calculated for comparison. Through the experiment, we found the reduction of each muscle activation is around 10% and more importantly, there is no sudden change in acceleration with the exoskeleton during the whole task and the RMS value of COP is generally reduced about 8% which confirmed the stability of the exoskeleton to carriers.

The remainder of this paper is organized as follows: In section 2, we established a biomechanical model of human bending over and analyzed the body movement mechanism to confirm the assistance of the exoskeleton theoretically. In section 3, we introduced a passive exoskeleton called 'MeBot-EXO'. We measured the changes in sEMG activity, COP and kinematic indexes of each task as the results of deploying the exoskeleton. Section 4 is the results and analysis part. Finally, Section 5 concludes the paper.

II. The Passive Exoskeleton

A. Structure Design

In this study, we evaluate a passive exoskeleton which is called 'MeBot-Exo' produced by MeBotX Intelligent Technology(Suzhou)Co.,Ltd. It is shown in Figure 1. It mainly consists of three parts: transmission shaft, energy generator and leg pads. Transmission shafts are used to transfer torque generated from energy generator. Energy generator is made up with gas springs. Its working principle is:

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when bending down and squatting, it will support the chest, give people resistance forces against the gravity and restore the gravitational potential energy into elastic potential energy. When getting up, it will release the elastic force to make people stand up more easily. In general, the exoskeleton is intended to transfer forces from the lower back to the abdomen and leg pads. The material of the exoskeleton is made up with aluminum alloy and nylon so that it can be convenient and lightweight. The mass of the full exoskeleton is just 2.5kg. Each of its joints have two degrees of freedom and the size of the gas spring is 800 N, it is approximately equivalent to a people's upper body weight. Lastly, the leg pads are made of the material witch is called ABS to provide enough friction between leg pads and thighs.

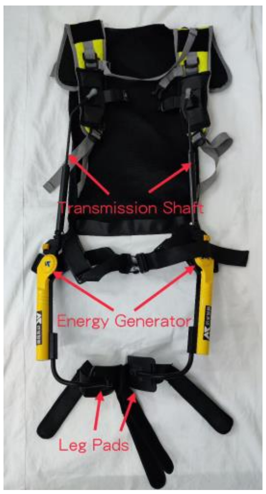


Figure 1. The components of the passive exoskeleton

B. Dynamics Design

Chaffin and Anderson's back force model [8] is adopted to test the feasibility and effectiveness of a control algorithm to minimize the erector spinae muscle force using a trunk-supporting exoskeleton at L5/S1 which is the body part between the 5th lumbar vertebra and the sacral vertebra.

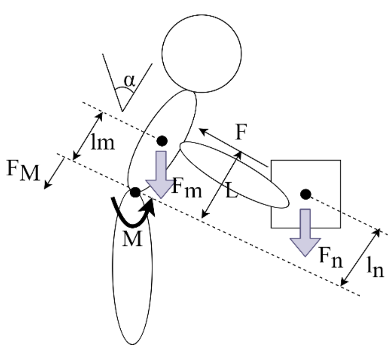


Figure 2. A simplified man is holding a box.

Figure 2 represents that a person is holding a box. The dynamic relationship can be obtained:

$$F_M = (F_m l_m + F_n l_n)\frac{g}{d}\sin\alpha - \ddot{\alpha}\frac{I}{d} \tag{1}$$

where F_M is the erector spinae muscle force, F_m and F_n are the mass of the upper body and lifted box respectively. l_m and l_n are the lengths of body and box from L5/S1 respectively, and d is the distance between the erector spinae muscle force and the spine center. α is the bending angel. g is the gravity constant.

To reduce the moment at L5/S1, a passive exoskeleton is used to provide a torque to help the lifting. With the exoskeleton, an extra force F is imposed on human's upper body. Based on this, Equation 1 is rewritten as:

$$F_M = (F_m l_m + F_n l_n)\frac{g}{d}\sin\alpha - \ddot{\alpha}\frac{I}{d} - \frac{FL}{d} \tag{2}$$

If the exoskeleton can provide a force F just as illustrated in Equation 3, it is shown that F_m can be zero theoretically in Equation 4.

$$F = \frac{1}{L}(g(F_m l_m + F_n l_n)\sin\alpha - \ddot{\alpha} I) \tag{3}$$

$$F_M = 0 \tag{4}$$

However, this cannot happen since almost all parameters in Equation 3 can't be measured or calculated precisely. But at least, it is shown that an exoskeleton can be indeed helpful when bending to lift things technically.

III. Experiment Setup

A. Participants

In this study, four healthy volunteers participated (all males, age: 23~26, weight: 70~75kg, height: 170cm~180cm) to perform our tasks. They are in good health and have no back injuries. The subjects have written informed consent before the experiment, and the study was approved by the ethics committee of Wuhan University of Technology.

B. Procedures

Subjects were asked to perform three actions with three different weights. The first action is to bend 40° with three different mass boxes which are 0, 5 and 10kg, respectively. The second action is to bend 90° with the same three heavy boxes. The last action is to semi-squat with the three same weights, too. Figure 3 shows the three movements. Then the muscle activation can be compared in many dimensions.

In the process of these movements, three types of data are collected. The first one is sEMG. A 16-channel equipment with a sample frequency of 1000HZ (ELONXI) is used (as shown in figure 5(a)), which components are: ① Main equipment of the EMG, ② Converter connection line, ③ Electrode interface converter, ④ Electrode connection line and ⑤ Wet electrodes. This equipment conveys its signal data by Bluetooth technology. In this study, the locations of two main lower back muscles are chosen which are (1) the left thorax thoracic erector spinae (LTTES), and (2) the right thorax thoracic erector spinae (RTTES), as shown in Figure 4.

(a) (b) (c)

Figure 3. Three different actions(a: bent 40°, b: bent 90°, c: semi-squat)

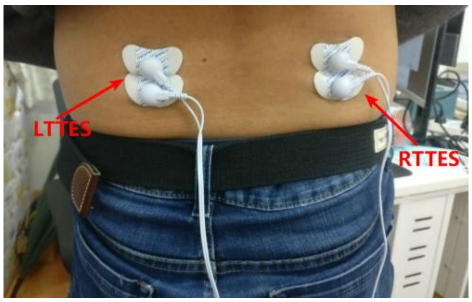
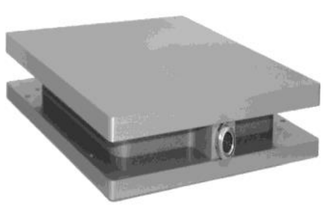


Figure 4. Two main waist muscles.

Kinematic data are collected using an 8-camera, 3D video-motion analysis system (Nokov) with a sampling frequency of 50 Hz, which is shown in figure 5(c).

Lastly, force and moment are also needed to calculate COP and potentially simulate in OpenSim [9] which is an open-source and free software to model, analyze, simulate and study human movement. A six-axis force platform (AMTI) (as shown in Figure 5(b) is used to collect three degree of freedom forces and moments.



(a) (b)

(c)

Figure 5. Three equipment used to collect data.

COP values of the X axis and Y axis in the horizontal direction are calculated through equation (5) and (6):

$$xCOP = (-1) \times \frac{M_y + F_x \times Z_{off}}{F_z} \tag{5}$$

$$yCOP = \frac{M_x - F_y \times Z_{off}}{F_z} \tag{6}$$

where *xCOP* and *yCOP* represent the COP values in the X-axis and Y-axis directions respectively; Z_{off} represents the distance from the sensor to the surface of the AMTI platform in the vertical direction, which can be consulted through the technical manual; F_x, F_y and F_z respectively represent the forces of X-axis, Y-axis and Z-axis directions; *Mx*, *My* and *Mz* represent the moments in the X-axis, Y-axis and Z-axis directions respectively.

C. Evaluation Principle

In this article, muscle activation is the mainly criterion to evaluate the effect of the presented exoskeleton. RMS (Root Mean Square) is probably the most common used index which can be presented as:

$$RMS = \sqrt{\frac{\sum_{i=1}^{N} x_i^2}{N}} \tag{7}$$

where N is the total data number, i is the index of the i-th data x_i which is the muscle activation level in this study.

In order to obtain the amplitude of muscle activation, Maximum Voluntary Contraction (MVC) value of the muscle needs to be measured firstly, and then use the following formula to calculate the amplitude of muscle activation of the corresponding muscle. The formula is given as:

$$Activation(i) = \frac{x_i}{MVC} \tag{8}$$

where *MVC* is a constant which can be measured before the experiments. x_i is the sEMG data at time i.

IV. Result and Discussion

Three representative situations are selected to explain and analyze the experimental results. The three situations are: ① bending over 40° with 0kg mass; ②bending over 90° with 5kg mass; ③semi-squat with 10kg mass. Full dataset, figures and scripts for Matlab can be downloaded from https://github.com/5by2by1by/2021ARM. In order to analyze the changes among these situations, RMS is adopted to demonstrate the differences. Figure 6, 7, 9 shows the LTTES muscle activation in the three different situations.

In Figure 6, the situation 1 is decomposed into two phases, which are: standing upright to bending over 40° (stage 1) and returning to the initial position after getting the mass (stage 2). In stage 1, when the exoskeleton is put on, the degree of muscle activation is lower and gentler. In stage 2, when the exoskeleton is engaged, the level of muscle activation at the moment of getting up is similar to that without the exoskeleton, but during the whole process of getting up, the muscle activation is still less when wearing the exoskeleton.

Figure 7 is the sEMG changes with and without exoskeleton in the situation 2, and Figure 8 is the corresponding actual movement. It is divided into four phases which are: from the initial state to touching the mass (stage 1), from lifting the mass to the upright state (stage 2), from the upright state to putting down the mass (stage 3), and from putting down the mass to the initial state (stage 4). In stage 1 and 3, it is shown that the exoskeleton does not bring obvious effort-saving effects and even sometime more costly instead, but in stage 2 and 4, it can be seen that the effect of the exoskeleton is very obvious, and the sEMG changes are relatively stable and much lower. So, this verifies the working principle of the exoskeleton, that is, when bending over to carry heavy objects, subjects need to overcome the resistance provided by the exoskeleton, and the corresponding muscles need to activate more; but when lifting heavy objects, the exoskeleton will release elasticity to help lift heavy objects. As a consequence, the result is that the second and fourth phases of muscle activation are more obvious saving with the exoskeleton, but in the first and third phases, the exoskeleton is not very helping with the lifting task.

Figure 9 shows the changes of muscle activation in the situation 3. The analysis result is almost the same as the second case, so the general analysis can be neglected, but it is worth noticing that the third movement costs more than the second one whatever the subject is wearing or not. There is a tip that the angles in these figures calculated by Nokov system are not explicitly the same as illustrated with the titles. These angles play a guidance role so that the phases can be divided more correctly.

And Figure 10 shows the corresponding RMS values to each situation. As can be concluded:

1) With the same weight, the greater the degree of bending, the greater the amplitude of muscle activation;

2) With the same action, the heavier the weight, the greater the amplitude of muscle activation;

3) With the same weight and action, the activation of the muscle is obviously lower when the exoskeleton is worn than that without the exoskeleton, and the change trend is relatively gentle and stable;

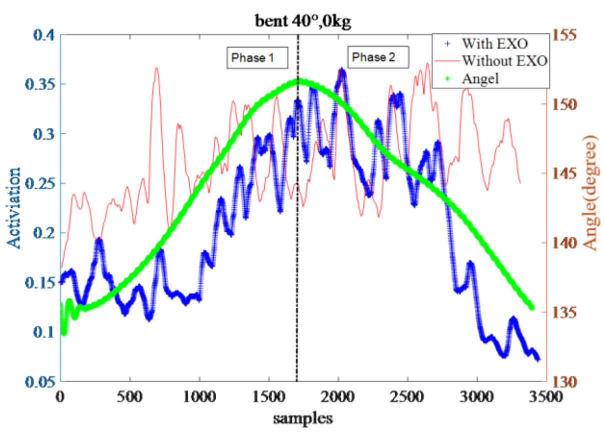


Figure 6. The change of LTTES muscle activation with no mass and bening 40°.

From figure 10, we can see that there is not that much difference among three actions. It is assumed that:

1) The time of every experiment is not exactly the same, so the whole process may contain some useless data which are very small. But in order to ensure the completeness and continuity of the experiment, these data are kept.

2) The muscles do not contribute much with a passive exoskeleton because of the muscle synergies [10]. Due to the existence of a rigid exoskeleton, the mechanics of body may have changed. Since the exoskeleton is activated by the muscular activity of the erector spinae, subjects must adjust their coordination to activate the exoskeleton at a speed that is comfortable for them.

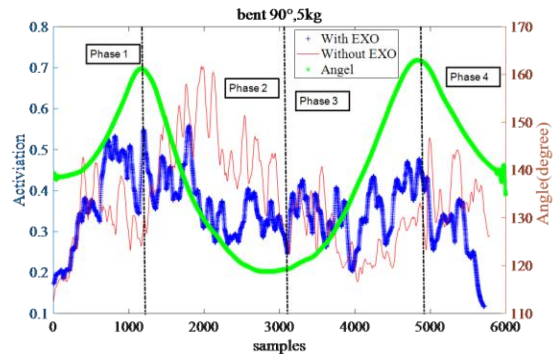


Figure 7. The change of LTTES muscle activation with 5kg mass and bening 90°.

Figure 8. Four phases during bending 90° action.

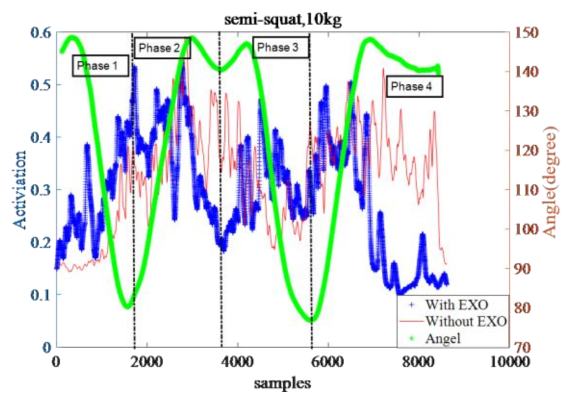


Figure 9. The change of LTTES muscle activation with 10kg mass and semi-squatting.

In addition, from figure 10, with the same weight (for example, mass = 5kg), it is not only shown that the greater the degree of bending, the greater the amplitude of muscle activation, but the muscle activation level is reduced by about 10% when the exoskeleton is worn than without the exoskeleton which verifies the positive effect of the passive exoskeleton.

COP represents the center of pressure on feet which is utilized in this study. This index is used to analyze the effect of the passive exoskeleton by judging the changing trend and RMS values of COP. If COP changes less and more stable, and basically the more positive effect of the exoskeleton is shown.

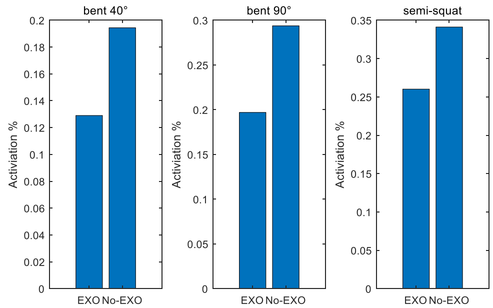


Figure 10. RMS values under three different situations.

Figure 11-13 show the changes of COPs with different weights and movements. In order to show the details of the COP's change, one situation (10kg mass) is chosen to analyze COP's change on the effect of the passive exoskeleton and the result is depicted in TABLE I. In this table, two evaluation standards are used, one is RMS and the other is range which is obtained by subtracting the minimum value from the maximum value. It can be basically seen that:

1) With the same weight, the greater the degree of bending, the greater the COPs' change;

2) With the same action, the heavier the weight, the greater the changes in COPs. This phenomenon is more reflected in yCOP, while the change in xCOP is small;

3) With the same weight and action, the COPs of wearing the exoskeleton is obviously slightly smaller than that without the exoskeleton, but with heavier objects, the COPs change trend is almost the same.

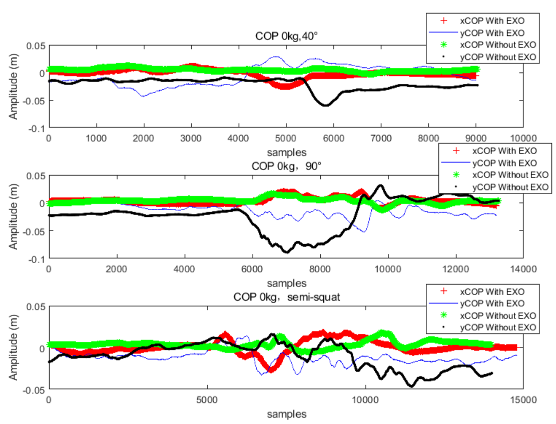


Figure 11. xCOP、yCOP's change with and without exoskeleton under 0kg mass situation.

At last, in order to compare the changing trends of kinematics with and without the exoskeleton, the changes of the velocities and accelerations are evaluated. In order to emphasis and stand out the point, one situation (10kg mass, bent 90°) is chosen, the corresponding kinematics features are shown in figure 14.

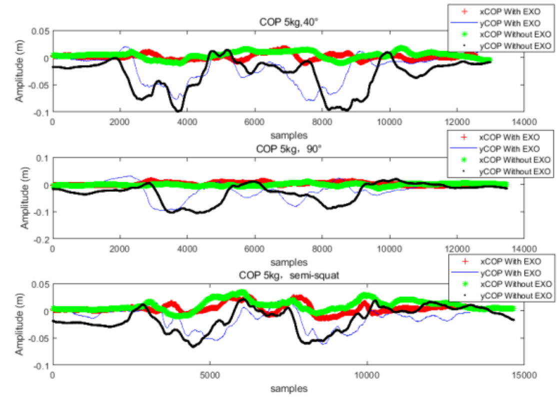


Figure 12. xCOP、yCOP's change with and without exoskeleton under 5kg mass situation.

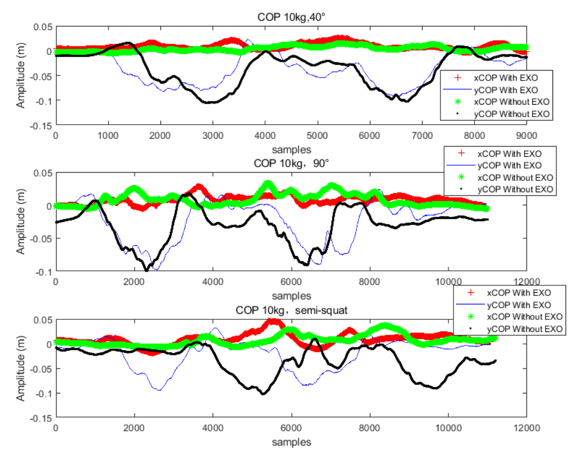


Figure 13. xCOP、yCOP's change with and without exoskeleton under 10kg mass situation.

TABLE I. RMS VALUES OF COP UNDER DIFFERENT SITUATIONS

Situations	RMS xCOP	RMS yCOP	Range (xCOP yCOP)
10kg, 40° (No-EXO)	0.0058	0.04022	0.02087 0.1211
10kg, 40° (EXO)	0.0091	0.0375	0.0295 0.1147
10kg, 90° (No-EXO)	0.0107	0.0368	0.0397 0.1177
10kg, 90° (EXO)	0.0089	0.0356	0.0335 0.1220
10kg, semi-squat	0.011	0.0372	0.04477

(No-EXO)			0.1127
10kg, semi-squat	0.0109	0.0333	0.0655
(EXO)			0.1280

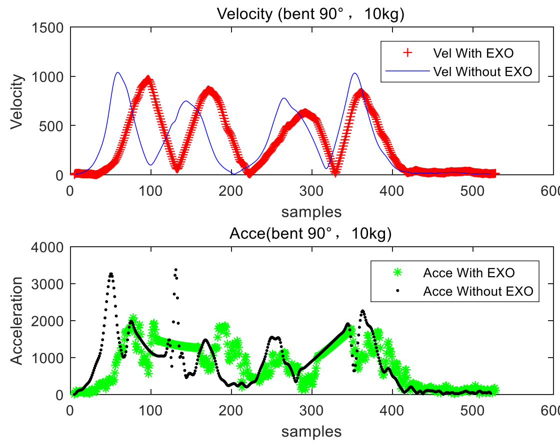


Figure 14. kinematics comparing with and without the exoskeleton

From the picture above, it is shown that with the same situation (10kg, bent 90°), there is still a difference in the kinematic changes between wearing and not wearing the passive exoskeleton. There is a big change in acceleration, but little difference in velocity. In the picture, when bending over to carry heavy objects, the acceleration is obviously higher without the exoskeleton, and there are also some big sudden changes. This shows that the passive exoskeleton has an explicit stabilizing effect on the human body.

V. Conclusion

In this paper, a way of accessing the passive exoskeleton is presented by posing three different movements with three different weights. The results show that wearing a passive exoskeleton has an obvious reduction in muscle activation than that without an exoskeleton, and the changes in COPs and kinematics features have also become more stable and smooth. So it is shown that the presented exoskeleton can help people's lifting easier and safer. Besides, by analyzing an action, a movement task is divided into four phases in order to tell the differences in detail. In this way, the principle and effectiveness of the passive exoskeleton are also confirmed.

However, there is still room for improvement. This passive exoskeleton is a rigid mechanical structure, which may affect other normal human movements. Secondly, after putting on the exoskeleton, it is not clearly that if it will cause damage to other parts of the body, especially the knee joints since these are the force points supporting the exoskeleton. In addition, this experiment has an obvious shortcoming, that is, the weight of the exoskeleton is not taken into consideration, which may reduce the relative effect of the exoskeleton.

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