Force and EMG power spectrum during eccentric and concentric actions

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ABSTRACT

KOMI, P. V., V. LINNAMO, P. SILVENTOINEN, and M. SILLANPÄÄ. Force and EMG power spectrum during eccentric and concentric actions. *Med. Sci. Sports Exerc.*, Vol. 32, No. 10, pp. 1757–1762, 2000. **Introduction:** This study was designed to examine the force and activation levels of elbow flexor muscles during preactivated eccentric, concentric and isometric actions. **Methods:** Force, average EMG (aEMG), and the EMG power spectrum were investigated at different constant movement velocities ($1\ \text{rad} \cdot \text{s}^{-1}$, $2\ \text{rad} \cdot \text{s}^{-1}$, $3\ \text{rad} \cdot \text{s}^{-1}$, and $4\ \text{rad} \cdot \text{s}^{-1}$) at different joint angles. **Results:** Average force at a 110° elbow angle was lower and aEMG was higher in concentric actions as compared with eccentric and isometric actions. At a 55° elbow angle, there was no difference in aEMG, or it was slightly higher in eccentric actions. MF was higher in the concentric as compared with eccentric actions at the three fastest velocities at the 110° elbow angle, whereas no difference was observed at the 55° elbow angle. In concentric action, MF was higher in $4\ \text{rad} \cdot \text{s}^{-1}$ in comparison with $1\ \text{rad} \cdot \text{s}^{-1}$ at 110° elbow angle. **Discussion:** These results suggest that it is difficult to maintain the maximal eccentric force throughout the whole range of motion. Maximal EMG activity and frequencies of the EMG power spectrum can be at the same level or lower in eccentric actions as compared with concentric actions, depending on the joint angle and preactivation mode. The results of the EMG power spectrum do not support the concept that in maximal eccentric actions fast units are selectively activated. **Key Words:** ISOKINETIC, aEMG, MOTOR UNIT RECRUITMENT

Muscle tension in concentric actions has been shown to decrease when the movement velocity increases (e.g., 18,42). In eccentric actions, the tension is greater and is less affected by changes in velocity in comparison with concentric actions (6,18). Although the forces are greater, it seems that there is some neural inhibition and it may be harder to fully activate the muscles in eccentric actions (41). Therefore, maximal isometric force can be similar or even exceed the maximal eccentric force (32,36,40). In addition, maximal EMG activity may be greater in concentric actions (12,37,39), in eccentric actions (M. Grabiner, personal communication) or at the same level (18), depending on the muscles, joint angles, and protocols used.

With some exceptions, in most motor functions there seems to be an orderly recruitment of motor units. The neurons with small slow conducting axons innervating slow contracting fatigue-resistant muscle fibers appear to be recruited before neurons with large fast conducting axons innervating fast contracting fatigable muscle fibers. This size principle was first described by Hennenman et al. (15,16), and it has later been shown to be valid both in isometric (9,13,24) and in dynamic (10,44) situations. In eccentric situations, however, changes in recruitment patterns have been reported (27). In rapid movements, slow-twitch muscles have become inactivated, whereas the activity of the fast-twitch muscles has been augmented (33). This possible change in activation within one muscle may also be velocity dependent (5,14,26). The use of an EMG power spectrum is an easy noninvasive way to estimate changes in different muscle actions and may give information on motor unit activation. Frequencies of the EMG power spectrum are related to the average conduction velocity of the active muscle fibers (2), and muscle fiber conduction velocity is higher for fast-twitch fibers (1). Therefore, a shift of the power spectrum to high frequencies would represent an increase in the average conduction velocity and thus greater use of fast units.

The purpose of this study was to examine the effects of different movement velocities in concentric and eccentric actions on muscle tension, average EMG amplitude, and the EMG power spectrum.

Figure 1—The ergometer subject system.

METHODS

Nine male subjects aged 18–27 yr volunteered to participate in the study. The mean height, body mass, and body fat were 187.0 (SD 7.8) cm, 78.8 (SD 9.9) kg, and 10.9 (SD 0.9)%, respectively. The subjects were physically fit basketball players. Full advice about possible risks and discomfort was given to the subjects, and they all gave their written informed consent to participate. The study was conducted according to the declaration of Helsinki and was approved by the ethics committee of the University of Jyväskylä. The subjects were seated in a chair, and their supinated right forearm was fixed to an isokinetic machine (Fig. 1). This ergometer is similar in principle to our previous equipment for different constant velocities in concentric and eccentric actions (12,18,19). It was specifically designed and constructed in our laboratory for research purposes only. No gravity correction has been installed in the dynamometer. The present ergometer can be used for both elbow and knee joint movements and can involve both flexors and extensors. It is driven by a powerful servomotor, which has necessary feedback control for position and velocity. The range for effective constant angular velocity is from 0 to 13 rad·s^{-1}. The desired velocities can be reproduced reliably as indicated by the low CV% (0.8–3.2%) both between eccentric and concentric action times at different angular velocities and between two consecutive attempts at certain velocity with maximal loading. The lever arm is equipped with the strain gauge transducer to measure the force applied on the wrist and ankle, respectively, for elbow flexion/extension and knee flexion/extension. The maximum recorded torques can be as high as 480 Nm. The high angular acceleration of 100 rad·s^{-1} assures reaching of the constant selected angular velocity in a very short period of time.

The range of motion of the elbow joint during the movement in the present study was from 55° to 165° in the eccentric actions (ECC) and from 165° to 55° in the concentric actions (CONC) (full extension = 180°). During the ECC the subjects were told to resist the movement of the machine and during the CONC to assist the lever arm movement. Four different velocities (1 rad·s^{-1}, 2 rad·s^{-1}, 3

rad·s^{-1}, and 4 rad·s^{-1}) were used in both conditions. All actions were performed maximally throughout the movement with an approximately 1-s maximal preactivation phase. (Fig. 2). Trials were performed in a random order with two consecutive attempts at each condition and a resting period of 2 min between the trials.

Maximal force was recorded with a force transducer throughout the motion. In isometric action (ISOM), maximal force was measured in the middle of this movement range at a 110° elbow angle and at 55° and 165°, which correspond to the starting angles of the ECC and CONC, respectively. The range of motion was divided into five 22° sections (66°, 88°, 110°, 132°, and 154°) for further analyses of force and average EMG (aEMG) (Fig. 2). Electromyographic activity (EMG) was recorded from the biceps brachii (BB), brachioradialis (BR), and triceps brachii (TB) muscles of the right arm. Bipolar (20-mm interelectrode distance) surface EMG recording (Beckman miniature-sized skin electrodes, USA) was employed. The electrodes were placed longitudinally on the muscle approximately halfway from the motor point area to the distal part of the muscle. EMG signals were recorded telemetrically (Glonner Biomes 2000, Germany) with a sampling frequency of 1000 Hz. Fast Fourier transformation (FFT) windows (Mega Electronics, Finland) with 50% overlap were used to analyze the whole range (110°) of motion. The window length was set according to the movement velocity so that with 4 rad·s^{-1} it was 128 points (9 windows), with 3 rad·s^{-1} and 2 rad·s^{-1} it was 256 points (6 and 8 windows), and with 1 rad·s^{-1} it was 512 points (7 windows). Median frequency (MF) was calculated for each window. The average of the three windows at the halfway point of the movement was used for further analyses.

Statistical analyses. Data were analyzed with an analyses of variance using a SPSS analyzing program. ANOVA with Method/Unique (also called sums of squares Type III), which uses the regression method to partition sums of squares was used. Multiple comparisons between velocities ($N = 6$) and between types of work ($N = 3$) were made according to Bonferroni's method with a significance level of $P < 0.05$. To test the reliability of the measurements,
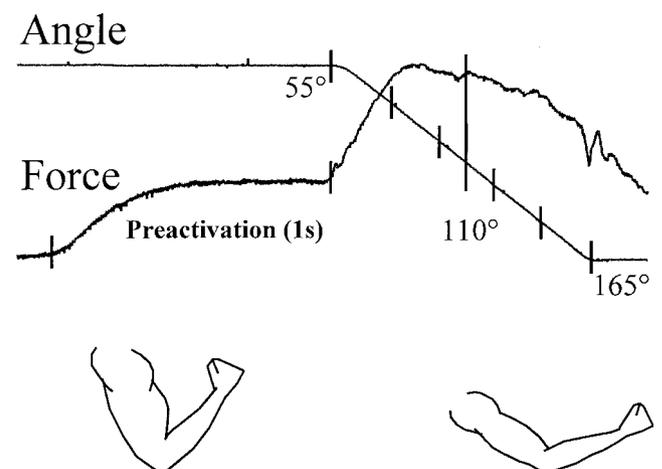

Figure 2—An example of the preactivation phase before eccentric action.
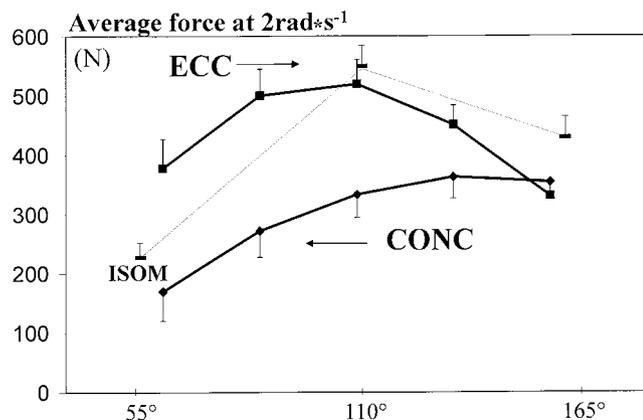
Figure 3—Average force in eccentric (ECC), isometric (ISOM), and concentric (CONC) action at 2 rad·s⁻¹.

correlations (Pearson) and coefficients of variation (CV) were calculated for each variable between two consecutive attempts. CV was expressed as a percentage (CV% = $100\sqrt{\sqrt{\Sigma di^2/2n/x}}$), where d is the difference between the two results in each individual, n is the number of subjects, and x is the mean obtained from all the subjects (23).

RESULTS

The results indicated an angle specific response of both maximum force and maximum EMG activity (Figs. 3 and 4). The average force was always the greatest somewhere in the middle of the movement regardless of velocity and direction. In the CONC at all velocities, the force was higher ($P < 0.001$) at the greater joint angle (154°) than in the flexed position (joint angle 66°), whereas in the ECC the behavior was not constant (Fig. 3). At the two slowest velocities, aEMG of all the three muscles was significantly higher ($P < 0.01$) at the flexed position compared with the greater joint angle both in CONC and ECC actions (Fig. 3). Although Figures 3 and 4 present the results from only one velocity (2 rad·s⁻¹), the pattern was similar at the other velocities as well. EMG activity was generally greater in the CONC than in the ECC actions at all joint angles except in the smallest one (66°) (Fig. 4). aEMG of the BR muscle
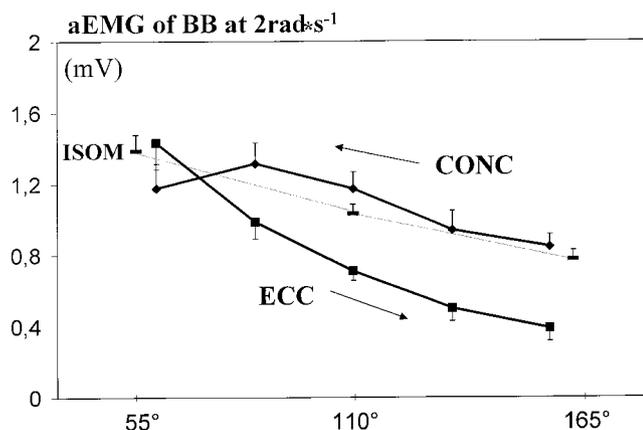

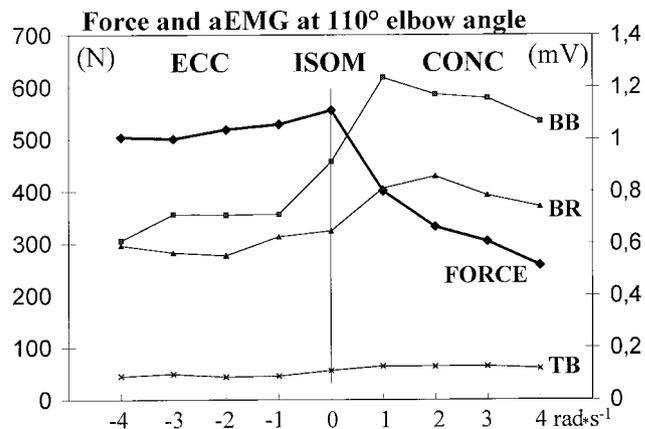Figure 4—aEMG of biceps brachii (BB) in eccentric, isometric, and concentric action at 2 rad·s⁻¹.

Figure 5—Force and aEMG of biceps brachii (BB), brachioradialis (BR) and triceps brachii (TB) with different movement velocities in eccentric, isometric and concentric action at elbow angle 110°.

followed, in general, the same pattern as that of the BB muscle.

At the 110° elbow angle, which represents the middle portion of the movement (see Fig. 3), the average force was significantly lower ($P < 0.001$) in the CONC in comparison with the ECC and the ISOM at all velocities and lower in the ECC than in ISOM at 3 rad·s⁻¹ and at 4 rad·s⁻¹ (Fig. 5). In the CONC actions, the force was the greatest at the slowest velocity and the effect of velocity was significant ($P > 0.001$), whereas the ECC forces, when averaged for the 110° point, were not velocity dependent. aEMG of the BB, when compared at this same angular position, was significantly higher ($P < 0.001$) in the CONC compared with the ECC at all velocities and higher ($P < 0.05$) than in the ISOM at the three slowest velocities (Fig. 5). aEMG of the antagonist muscle TB was significantly higher ($P < 0.05$) in the CONC compared with the ECC at 1 rad·s⁻¹ and 2 rad·s⁻¹. No significant differences in aEMG were observed when comparing different velocities separately either in the ECC or in the CONC.

In the ISOM at different joint angles, the maximal force was highest at 110° and lowest at 55° ($P < 0.001$). aEMG of all three muscles was significantly higher ($P < 0.001$) at 55° compared with 165°, exceeding also the values of 110°. Table 1 summarizes the results of the ISOM actions.

MF in the BB and in BR was significantly higher ($P < 0.01$) at 66° as compared with the 154° elbow angle in the ECC at all velocities and in the CONC at 1 rad·s⁻¹. Figure 6 shows the MF of the BB at different joint angles in the CONC and the ECC with the velocity of 2 rad·s⁻¹.

When the middle part (110°) was again taken as a reference angle, MF of the BB was significantly lower ($P < 0.05$) in the ECC than in the CONC at the three fastest velocities, whereas no differences were observed when comparing either CONC or ECC with ISOM. In the CONC, MF of BB was higher ($P < 0.05$) in 4 rad·s⁻¹ than in 1 rad·s⁻¹ (Fig. 7). No significant differences were observed in MF of the BB and the BR in the ISOM at different joint angles.

TABLE 1. Maximal force and aEMG in isometric action at different joint angles.

Elbow Angle	Max Force	aEMG BB	aEMG BR	aEMG TB
55°	249 ± 70 N	1.41 ± 0.42 mV	0.83 ± 0.38 mV	0.15 ± 0.11 mV
110°	545 ± 141 N	1.00 ± 0.23 mV	0.72 ± 0.45 mV	0.12 ± 0.09 mV
165°	451 ± 104 N	0.81 ± 0.29 mV	0.61 ± 0.30 mV	0.09 ± 0.02 mV

The CV% was usually smallest and the correlation highest at the slowest velocities and at the elbow angle in the middle part of the movement. The range of CV% at the 110° elbow angle of two consecutive attempts for the average force, aEMG, and MF in different conditions is shown in Table 2. The correlation between two attempts was significant for force ($P < 0.001$), for aEMG ($P < 0.01$), and for MF ($P < 0.05$) for all the muscles at all the conditions with a few exceptions regarding MF in the BB muscle.

DISCUSSION

When comparing eccentric and concentric performance, a joint angle representing the middle part of the motion is often chosen as a reference for comparisons (e.g., 18). A similar approach was used also in the present study. The force values were higher in the ECC as compared with the CONC in which the force decreased with higher velocities. The results regarding the ECC and the CONC are similar to previous studies (e.g., 11,12,18,32,37). However, in the present study, the ECC force did not exceed the ISOM force, which has been reported earlier for the knee extensors (36,40) and for the forearm extensors (32). The present results, as well as other recent data (22), suggest that if the force is measured immediately after the onset of the stretch ECC force exceeds the ISOM force, regardless of the starting angle. aEMG was higher during the CONC than the ECC in the middle part of the motion contrary to some previous findings (Grabiner, personal communication, 18) but similar to others (12,37,39). However, in the flexed position, aEMG was similar in the ECC and the CONC, but in the ECC it decreased throughout the motion. The decrease was significant only at the two slowest velocities, suggesting that the longer the working time the greater the reduction. Maximal preactivation used in this study may
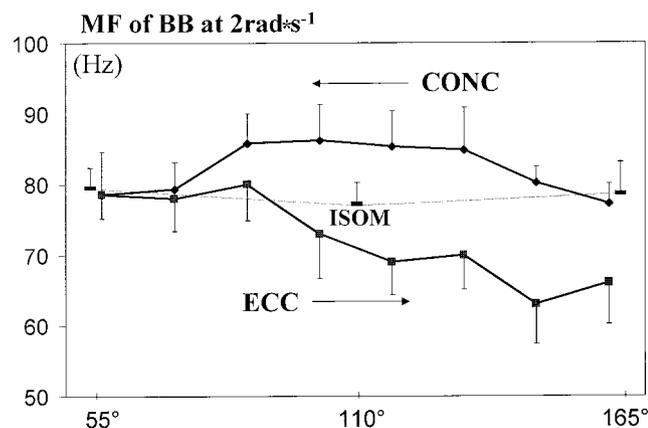
have played some role in this observed phenomenon. It is possible that the stretch-induced force output depends on how early the stretch occurs after the onset of activation (28). In the present study, the maximal preactivation period (1 s) before the onset of either the ECC or the CONC was longer than that used by Komi (18). The mechanism responsible for causing a reduction in muscle activation when the muscle is stretched is not clearly known, although some suggestions have been given in the literature (17,30).

The frequency component of the EMG power spectrum followed the same pattern as that of aEMG. At the flexed position no difference in MF was observed between the ECC and the CONC, but in the middle part MF was significantly lower during the ECC. MF decreased during the ECC throughout the motion, suggesting changes in the muscle fiber conduction velocity and therefore possible derecruitment of some of the fast units. It has been proposed that the EMG power spectrum is more susceptible to changes in motor unit recruitment as opposed to changes in the firing frequency of the individual motor units (34). The power spectrum could also be affected by muscle length (25). An increase in muscle length leads to a decrease in the conduction velocity of the muscle fiber (29), which has been shown to be related to the frequencies of the EMG power spectrum (2). On the other hand, if fast-twitch units are selectively recruited in ECC actions (27) an increase in MF could be expected because muscle fiber conduction velocity is higher for fast-twitch fibers (1). When considering the elbow angle of 110°, which represents the middle part of the motion, our results are similar to others who have reported lower or equal frequencies during ECC as compared with
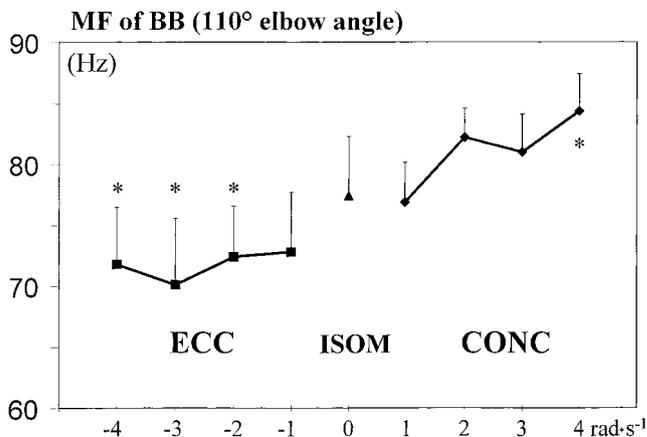

Figure 7—Median frequency (MF) of biceps brachii with different movement velocities in eccentric, isometric, and concentric action at elbow angle 110°.

Figure 6—Median frequency (MF) of biceps brachii in eccentric, isometric, and concentric action at 2 rad·s⁻¹.

TABLE 2. Lowest and highest CV% of maximal force, aEMG, and MF at the elbow angle of 110°.

	Lowest CV%	Condition	Highest CV%	Condition
Max force	3.1%	ECC 1 rad·s⁻¹	6.8%	CONC 4 rad·s⁻¹
aEMG BB	7.7%	CONC 3 rad·s⁻¹	17.4%	ECC 2 rad·s⁻¹
aEMG BR	0.6%	ECC 1 rad·s⁻¹	24.8%	CONC 2 rad·s⁻¹
MF BB	6.5%	CONC 4 rad·s⁻¹	12.0%	CONC 3 rad·s⁻¹
MF BR	5.7%	ISOM	16.8%	CONC 2 rad·s⁻¹

CONC either in submaximal (4,25) or in maximal (37,38) situations.

The EMG power spectrum has been used also to evaluate the changes in muscle activation at different movement velocities. The shift of the EMG power spectrum toward higher frequencies with higher movement velocities has been suggested to be due to differences in activation patterns (21,26,35). The significant increase in MF observed with the highest velocity during the CONC gives further support that some changes in the activation may have occurred. Because the skin acts as a low-pass filter (20), it is possible that some of the highest frequencies may have been attenuated. Whether the changes in the power spectrum are due to derecruitment of slow units or recruitment of additional fast units is difficult to estimate with the present methodology.

In a voluntary situation there is always some variation in the forces due to, for instance, motivation. Therefore, some changes in aEMG and the EMG power spectrum are to be expected for this reason. However, in an isometric situation the EMG power spectrum has been shown to be rather reliable even for measurements repeated over separate days (3,7,43). In the present study the high correlations between two consecutive attempts and rather low coefficient of variations, especially in the middle part of the motion and with low movement velocities, suggests that the EMG power spectrum is reproducible in dynamic situations as well. In dynamic actions it is possible that the electrode may change its location in relation to the innervation zone, which may affect EMG power spectrum (31). In the present study the range of motion was similar at all the velocities and the length of the FFT window was adjusted according to the velocity. Therefore the possible effects caused by electrode movement should be similar in both exercises. However, because the signal may be nonstationary, especially in fast movements with short FFT windows, one should be careful in interpreting the results (see, e.g., 8), and therefore further testing of reliability is suggested.

In conclusion, during ECC action as measured in the present study, it may be difficult to maintain the maximal force throughout the whole range of motion. Maximal EMG activity and frequencies of the EMG power spectrum can be on the same level or lower in ECC as compared with CONC, depending on the joint angle and preactivation mode. The results of the EMG power spectrum from this current study suggest that muscle fiber conduction velocity may be lower in eccentric actions than in concentric and higher with higher movement velocities in concentric actions. Lower MF during ECC compared with CONC could be explained, in part, by increased muscle lengths associated with ECC actions. Whether the behavior of median frequency can be used to interpret selective recruitment of motor units is yet to be determined.

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The purpose of the article is is to compare the frequency of the power spectrum and the amplitude of the surface electromyographic (EMG) signal of the biceps during eccentric and concentric contractions of different intensity to indirectly evaluate possible differences in movement recruitment. Materials and methods: the bioelectric activity of the biceps was studied during the flexion of the forearm with a bar. Eight trained men and one woman performed the exercise in eccentric and concentric modes of muscle contraction with an intensity of 100%, 80%, 50% and 25% of the maximum voluntary contractions. Methods: Force, average EMG (aEMG), and the EMG power spectrum were investigated at different constant movement velocities (1 rad x s(-1), 2 rad x s(-1), 3 rad x s(-1), and 4 rad x s(-1)) at different joint angles. Results: Average force at a 110 degree elbow angle was lower and aEMG was higher in concentric actions as compared with eccentric and isometric actions. At a 55 degree elbow angle, there was no difference in aEMG, or it was slightly higher in eccentric actions. MF was higher in the concentric as compared with eccentric actions at the three fastest velocities at the 110 degree elbow angle, whereas no difference was observed at the 55 degree elbow angle. In concentric action, MF was higher in 4 rad x s(-1) in comparison with 1 rads x s(-1) at 110 degree elbow angle. Despite possible inhibition in eccentric actions the relative force decrease after fatiguing maximal eccentric and concentric exercise can be similar after both exercise types provided that the movement is always started with maximal isometric preactivation. Key words: Eccentric, concentric, isometric, force, aEMG, median frequency, motor unit recruitment.

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