PROCESSING GAIT ANALYSIS DATA: A SOFTWARE SYSTEM FOR ESTIMATING THE VARIATIONS OF QUADRICEPTS DURING THE GAIT.

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Abstract: This research work presents a software system for estimating the length variation of the four muscles that compose the quadriceps of the human lower extremity. The experimental data are acquired by a gait analysis system. The gait analysis system includes among others six infrared cameras. The light coming from the cameras is reflected by retro-reflective markers that are attached to the lower limbs of the subject (e.g. a patient or an athlete). Then, signal processing takes place and a set of arithmetic values representing the 3D co-ordinates of the markers positions in the 3D space are calculated and are available for further processing. First we used these values to model the bone structures of the lower limbs. Afterwards, we estimated the muscle paths of the quadriceps based on their anatomical relationships to three-dimensional bone surface representations. Combining the muscle paths along with the orientation of the bone structures in the 3D space, we propose a method to estimate the lengths of the four muscles during the gait cycle, as well as their variations.

Introduction

The musculoskeletal system is responsible for the structural support and for the voluntary motion of the human body. The main structures of this system are muscles, tendons, joints, cartilages and bones and all these are combined with each other and contribute for the constitution of functional and moving joints. Muscles and tendons are able to actuate movement by developing and transmitting force to the skeleton and if for any reason (either pathological or not) they become dysfunctional, human movement is affected and patients are needed to undergo in surgical reconstructions.

A great number of diseases affects the neuromuscular and musculoskeletal systems, and may thus lead to disorders of gait. Among the most important we can refer cerebral palsy, parkinsonism, muscular dystrophy, osteoarthritis, rheumatoid arthritis, lower limb ampu-tation, stroke, head injury, spinal cord injury, myelo-dysplasia and multiply sclerosis. The reconstruction of a structure that participates in the gait procedure is not as easy as it might seem at a first glance. All structures are connected and collaborate with each other and the change of one parameter of one structure affects all the others. For instance, if a tendon is being lengthened or shortened even a few centimetres from the normal length, the muscle fibers may be too long or too short to generate satisfactory (active) force and as a result the movement becomes abnormal [1,2]. Because of that complexity, it is quite difficult for the surgeons to restore the function of the musculoskeletal components, without the help of an assistant tool.

Orthopaedic surgery uses a variety of diagnostic and assessment computational tools [3] for the diagnosis and the assessment of orthopaedic diseases or traumas. The most commonly used systems among others are *gait analysis systems, muscle and gait simulators* [4][5], *medical resonance images* (MRI) and *electromyography* (EMG). All of them are capable of monitoring the structures that make the movement dysfunctional by using different techniques. MRI images depict accurately the physiology of the muscles and EMG can give accurate information about muscles function by recording their electrical tension. Also, more elaborate systems such as simulators can simulate (model) the function of musculotendon structures, by extracting biomechanical property values such as muscle forces and joint moment arms. The extracted information then, compared with experimental data provides an indication of whether or not a change in the muscoloskeletal model can benefit the gait process.

The development of the software system presenting here emerged from the need of a tool that it could easily evaluate the pre-surgical condition of a patient and it could assess the surgery process (assess the surgery impact onto the muscle function). For this reason we proposed a methodology and we developed a software system that estimates in an easy and fast way the length variations of the four muscles of human quadriceps.

Essential for the pre-operative and post-operative evaluation of the patient condition is not the knowledge of the muscle lengths, but the muscle length variation instead. The knowledge of the above quantities can be used as an indication of the muscles' condition and therefore it can be applied for the: 1) the assessment of the post-operative patients' condition who have undergone to a surgery on the quadriceps 2) comparison of different surgical techniques 3) evaluation of athletes' condition and 4) measuring the influence of medicines to quadriceps muscles.

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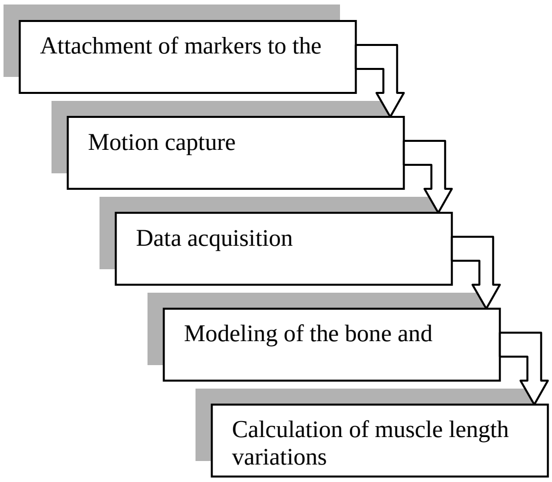

Figure 1: Work flow for the calculation of quadriceps length variations.

Materials and methods

The gait analysis system

The *VICON* gait analysis system was used for capturing subject's gait instances and it includes both hardware and software applications for analysing the motion capture. The main components of this system are the six infrared cameras and the workstation software that processes the recording of these cameras. The term "motion capture" refers to the procedure of gait (motion) recording by an array of cameras in order to reproduce the motion in a digital environment. The cameras record the motion of the markers attached in previously defined and well-known positions onto the limbs. The markers are lightweight spheres coated in retro-reflective tape and they have the ability to reflect the light stroke on them. Therefore, marker purpose is to track the motion.

The processing of the motion data returns the coordinates (arithmetical values) of the locations of the markers in the 3D space at each frame of the capture. These arithmetic values describe the paths that each marker has taken through the capture. As explained later (Section 2.3), by processing properly the extracted marker positions we generate the object motion in digital format so that we can thoroughly examine the function of the gait.

The proposed method for the calculation of the muscles variation

The method we propose for the calculation of muscle variation consists of two phases. In the *first phase* we model the lower extremities and the four muscles of the quadriceps, using as input data the motion acquired data of the gait analysis system. The scope of modelling the muscles is the calculation of muscle lengths. We have developed a model that we implemented in a computer program that reproduces the motion of the bones of the lower extremities in a digital format and after that we can apply the method of measuring the muscle lengths as will be described in Section 4 onto this model. In this way we get measurements of muscle lengths over the gait cycle. Also we can visualize the models of both bone and muscle structures in a lifelike way in a 3D virtual environment. For these applications we utilized two software packages of the VICON gait analysis system, which we used for capturing the motion (*BodyBuilder* and *Polygon)*.

In the *second phase* we feed the software system, which we developed with the extracted data from the previous step and finally we estimate the length variations of the four muscles during gait.

Representation of the bone structures of the lower extremities

We modelled seven basic structures that participate in the gait process: 1) Pelvis 2) Femur (right and left) 3) Tibia (right and left) and 4) Foot (right and left). Every segment was defined by a group of points, consisted by both real (markers) and virtual ones, which are moving together. These points hold constant the inter distances while the real segment is moving. For this reason we say that we modelled the segments as *rigid bodies*, although human body parts are not perfectly mechanically rigid, but maintain a factor of flexibility. Thus, when a segment is moving, all the points on it are moving simultaneously.

The minimum number of global points that was required for the definition of the orientation of a segment was three and these points should not been simultaneously in a straight line. After the definition of a segment, any other local points in the segment can be defined as global. In addition to this, the definition of new points, called *virtual points*, utilizing the orientation of an already modelled segment was the key for the modelling of both the bone and muscle structures.

For the definition of a segment we used a single point to represent its origin and three *segment axes* (Axis-1, Axis-2, Axis-3) for determining the orientation of the segment. At each frame of the motion capture, as the marker locations are changing, the local axes of each segment are redefined in view of the present -in that frame- 3D coordinates of the global points that determine the local segment axes. As a consequence, the modelling of a segment equals with the definition of three axes that are redefined in every frame of the motion capture.

Table 1: Points and coordinates defining the muscle paths of the quadriceps.

Rect us	Max	Min	Point 1	Point 2	Point 3	Point 4	Point 5
			{-29.5,-31.1,96.8}	**{33.4,-403.0,1.9}**	**{12.1, 43.7, -1.0}**		
			Pelvis	**Femur**	**Patella**		
				83.65 <ang<171.97			
V a s			**{14.0,-209.9, 18.8}**	**{35.6,-276.9, 0.9}**	**{37.0,-404.8, -12.5}**	**{27.4,-425.5, -13.1}**	**{6.3,44.5,-17.0}**
			Femur	**Femur**	**Femur**	**Femur**	**Patella**
					69.33<ang<101.99	**101.99 <ang<171.97**	
V a st			**{29.0,-192.4, 31.0}**	**{33.5,-208.4, 28.5}**	**{34.3,-403.0, 5.5}**	**{5.8,48.0,-0.6}**	
			Femur	**Femur**	**Femur**	**Patella**	
					81.36<ang<171.97		
V a st			**{4.8,-185.4, 34.9}**	**{26.9,-259.1, 40.9}**	**{36.1,-403.0, 20.5}**	**{25.3,-424.3,18.4}**	**{10.3,42.3, 14.1}**
					69.33<ang<110.01	**110.01<ang<101.9**	
			Femur	**Femur**	**Femur**	**Femur**	**Patella**

In the following lines is given the pseudocode that implements the modeling of the human segments throughout the motion data.

```
for frame = Firstframe till frame =Lastframe
   do
      define the  segments
//…based on the location of markers. This is the
//stage where pelvis, femur, patella, tibia and foot are
//defined as rigid bodies. Actually the only thing that
//takes place is the definition of the three local axes of
//each segment in order later muscles can be located
// in regard with these frame of reference.
     frame = frame + 1 //go on to the next frame
enddoloop
endforloop
```

Table1 defines the muscle paths of the quadriceps. *Max (Min)* is the maximum (minimum) number of path points that one muscle can have. The triplet {…} under the PointX is the 3-dimentional co-ordinates of PointX. The segment named *Segm* under the triplet of *PointX* gives the information that the values of the co-ordinates are referred to the *Segm's* frame of reference. The arithmetic expression under segment name (if exist) indicates that when it is true, the point of the same column should be included in the muscle path.

By saying *definition* of a segment we mean that each segment is a different *object*, which has a *name* and some *attributes* that include among others the segment origin and the segment coordinate system (Axis-1, Axis-2, Axis-3).

Representation of the four muscles of quadriceps and calculation of their lengths

In order to determine the location of the four muscles during the gait we used a method where the muscles are defined as a sequence of straight segments. This sequence does not remain static during the gait, but varies as long as the muscles are activated. For the definition of these segments we used the *muscle paths* of the quadriceps muscle [1],[4],[5]. The term muscle path refers to a set of ordered 3D points, which form a series of line segments. Every segment consists of two points, therefore the definition of one segment requires two points, two segments of the same muscle requires three points and so on. The points of a muscle path are defined relative to the bones that the muscle crosses. Also the number of muscle path points in each frame depends on the flexion-extension angle, which is formed during the gait between the femur and tibia (Figure. 2, 3). Whenever the knee flexes, the muscle wraps over the patella structure and as a result it is lengthened. Therefore, the greater the knee flexion angle is the longer the muscles are.

Thus in order to calculate the length of each muscle for each frame, firstly we calculate the flexion-extension angle. Then, according to the estimated value of this angle we define how many points the path of each muscle should have. As every segment is moving in the 3-D space, it is obvious that it can be moved over its three local axes (Axis-1, Axis-2, Axis-3). The most common way to express rotations in the space is to compute the three Euler angles. Lower limb can rotate about the knee joint creating three types of angles. The possible rotations of knee joint are [6]:

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1) *flexion* and*extension* which take place in the sagittal plane, 2) *abduction* and *adduction* which take place in the frontal plane and 3) *internal* and *external* rotations which take place in the transverse plane.

Although during the gait all the three rotations can take place, we assumed that only the knee flexion angle occurs because the other two angles are negligible during the gait process.

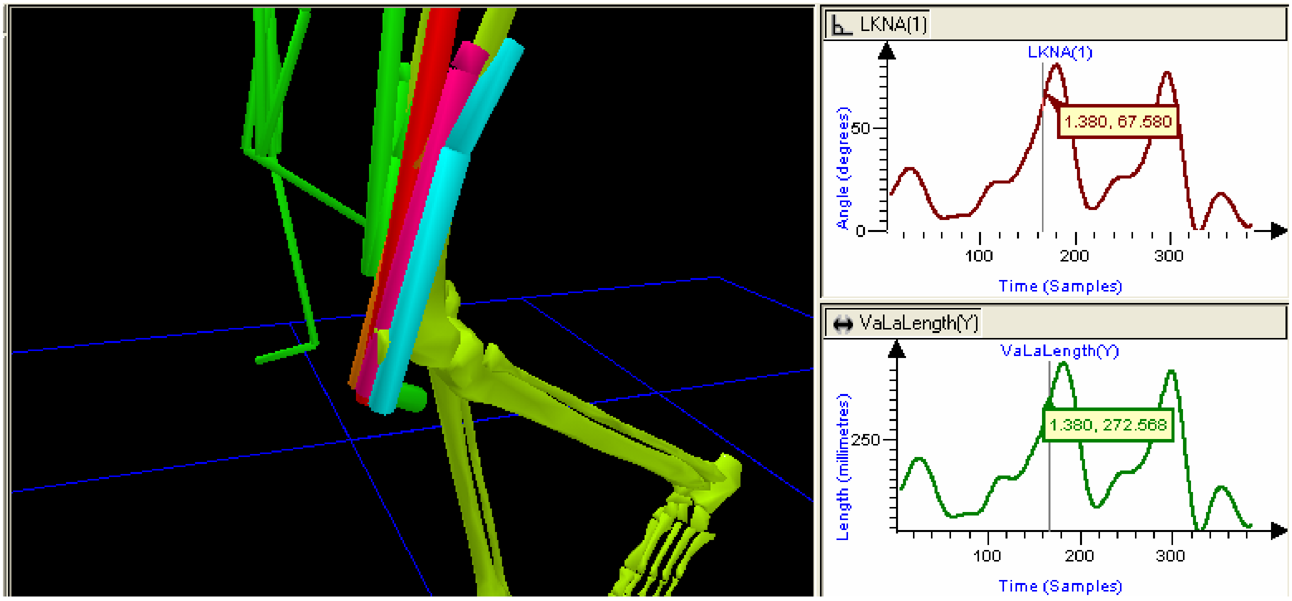

Figure 2: Modeling the lower limbs and quadriceps muscles in a 3D environment. The flexion angle in this frame of motion capture is 67 degrees.

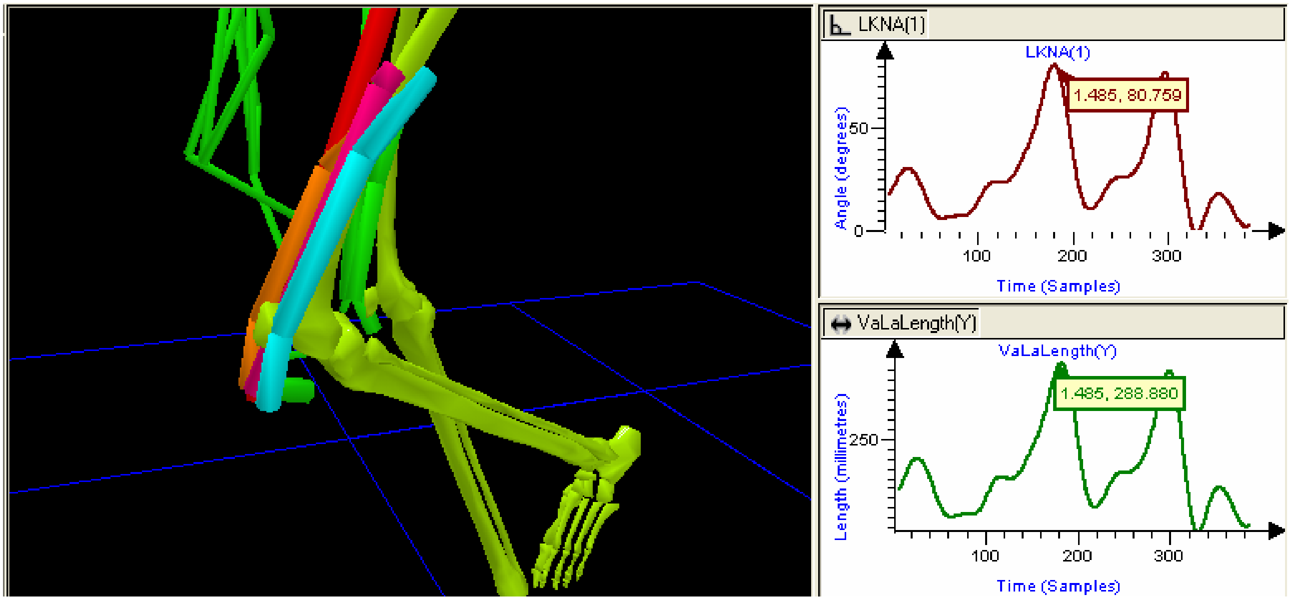

Figure 3: Modeling the lower limbs and quadriceps muscles in a 3D environment. The flexion angle in this frame of motion capture is 80 degrees.

After, the computation of the knee flexion angle, we determined how the muscle paths would be defined in each frame based on the corresponding knee flexion angle. For instance if in a time sample the knee flexion angle is 80 degrees then the path of Rectus Femoris should be consisted of three points and not of two, because the knee angle is greater than 83.65 degrees (Table 1).

$$\boldsymbol{L}_m = \sum_{i=1}^{n-1} \left| \boldsymbol{P}_{i+1} - \boldsymbol{P}_i \right| \tag{1}$$

Equation 1 calculates the muscles length, implementing adding the distances between all the couples of the muscle path points. [4].

Where $\mathbf{P}_1$ to $\mathbf{P}n$ are the 3D co-ordinates of the points, which are used to define the muscle path and $\mathbf{L}_m$ is the overall calculated muscle length.

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Our implementation of the calculation of the muscle paths could be described by the above pseudocode:

```
for frame = Firstframe till frame = Lastframe
   do
      define segments
      calculate kneeFlexionAngle

      define Rectus Femoris path
     define Vastus Medialis path
     define Vastus Intermedius path
     define Vastus Lateralis path

     calculate muscle lengths
   frame = frame + 1

enddoloop

endforloop
```

In the case of the calculation of Rectus-Femoris path according to the Table 1, the pseudocode is:

```
RectFemOrigin = {-29.5, -31.1, 96.8}
    //in regard to the reference frame of pelvis
RectFemInsertion = {12.1, 43.7, -1.0}
 //in regard to the reference frame of femur
If  KneeFlexAng > 83.5 and  KneeFlexAng > 171.97
     RectFemMed = {33.4, -403.0, 1.9}
      //in regard the reference frame of femur
     NumPointsofRectFemPath = 3
EndIf
Else
    NumPointsoRectFemfPath = 2
EndElse
```

and the muscle length is:

```
If NumPointsoRectFemfPath =2
  RectFemLength =
    distance(RectFemOrigin, RectFemInsertion)
EndIf
Else
  RectFemLength =
    distance(RectFemOrigin, RectFemMed ) +
   distance( RectFemMed, RectFemInsertion)
EndElse
```

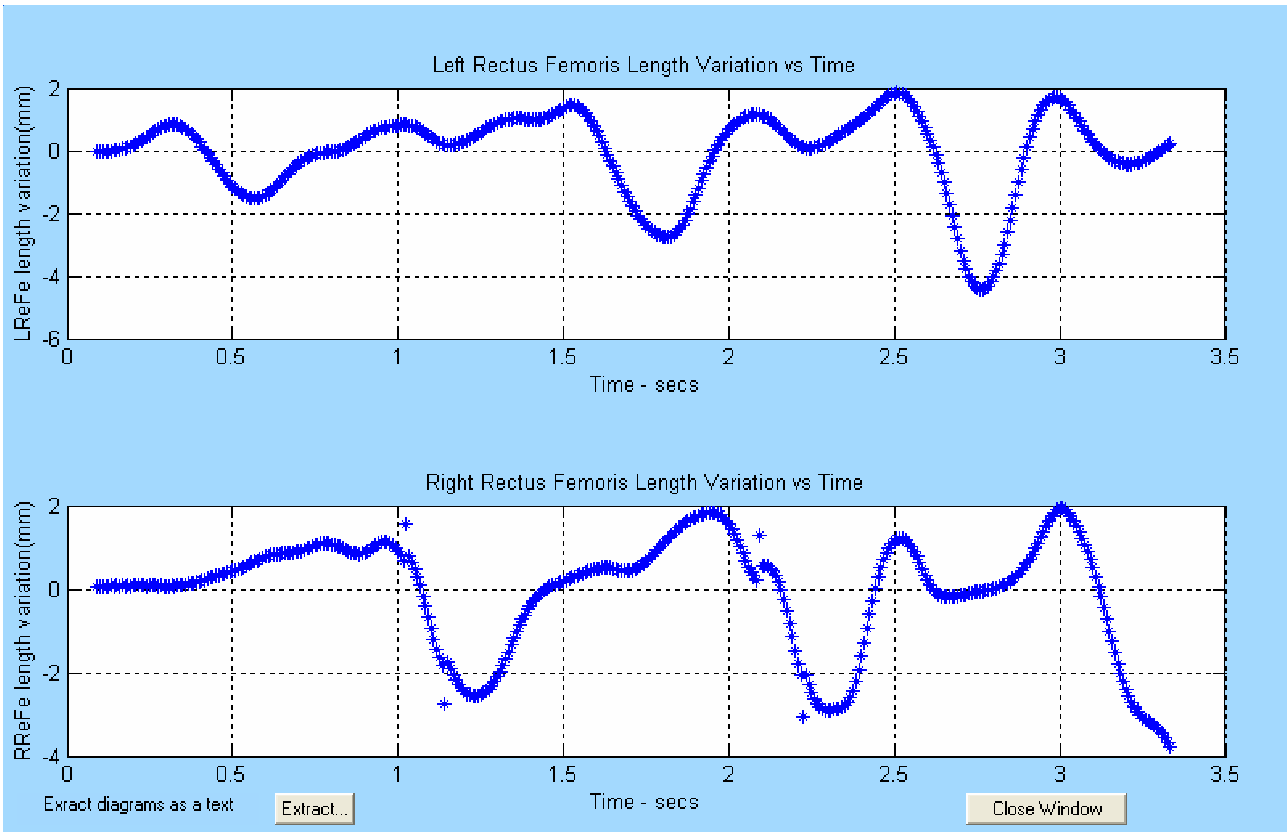

Figure 4: Rectus Femoris length variation (mm) vs. time (sec).

Calculation of quadriceps length variations

Our software tool takes as input the arithmetic values of the lengths of the four muscles at each frame that have been estimated at the previous step. Then, it calculates the length variation and length rate variation vs. time and knee flexion angle and vs. both the time and knee flexion angle. The system provides to the user the ability to examine 96 different plots (muscle length vs. time, muscle length vs. knee flexion angle, muscle length vs. knee flexion angle vs. time, muscle length

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variation vs. time, muscle length variation vs. knee flexion angle, muscle length variation vs. knee flexion angle vs. time, muscle length rate variation vs. time, muscle length rate variation vs. knee length rotation and muscle length rate variation vs. knee flexion angle vs. time) or to extract all the above quantities in text format (Figure 4).

The variation of muscle length was calculated according to the formula:

$$\Delta_l = l_{t+1} - l_t \tag{2}$$

where l_t is the muscle length at time sample t and Δ_l is the muscle length variation at time sample $t+1$.

The muscle length rate variation was computed using the expression:

$$U = \frac{\Delta_l}{\Delta_t} = \frac{l_{t+1} - l_t}{\Delta_t} \tag{3}$$

where Δ_t is the time between two samples, and with U we denote the muscle length rate variation.

Conclusions

The procedure of assessment the condition of patients or athletes muscles pre-operatively and post-operatively is very useful, firstly for the planning of a surgery and secondly for the evaluation of the operation. It is widely known that medical devices such as magnetic tomography can do provide medical images where muscle lengths are accurately depicted, but unfortunately it is very difficult and costly to apply them during motion. The system that we developed gives an easy and fast way of computation the variations of the lengths of the quadriceps providing the doctors a good evidence of muscles condition. This system can also be used as an assessment tool for comparing different surgical techniques and easily can extend for the other muscles of human lower limbs.

As further work we have left the extension of the software so that it can model a wider range of muscles and not only the quadricepts. It would be also interesting to compare our estimates with the results of more sophisticated but computationally consuming systems such as simulators so that we can assess the system accuracy.

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