EVALUATING THE HUMAN JOINT LAXITY USING STEWART PLATFORM MECHANISM

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Abstract

Chronic laxity may cause the complications of instability including arthritis and pain with long term loss of function.

The aim of this study is to measure the elbow joint laxity using a newly developed Stewart platform device. The device measures trajectory data which may correlate with the joint laxity.

The study hypothesis relates the displacement of joint center of rotation to joint laxity. However, because of tissue dynamics in the live organs, the center of joint rotation moves. The device traces the center of the joint rotation in each increment phase of motion to plot a trajectory for the center of the joint during a normal joint motion.

Having this device in a clinical setting could give accurate information about joint laxity. This could determine whether or not to proceed with surgery to correct laxity.

Introduction

Kinematics of the elbow joint occupies a considerable place in orthopedic surgery. Many devices have been constructed with this aim. Hand goniometers were formerly employed for measuring elbow kinematics [1]. Morrey and Chao studied the motions of the elbow joint [2]. They measured elbow flexion and forearm rotation by using an electronic goniometer. Another study was published by Morrey and Chao for calculating elbow joint with the help of biplanar roentgenograms [3]. They obtained three-dimensional kinematics of the joint in their research. Tanaka et al. used electromagnetic motion tracking data and described the first three-dimensional elbow kinematic [4]. Lateral roentgenograms used a kinematic analysis of elbow kinematics by London [5]. In this research, London used a special Reuleaux technique for analysis. The Reuleaux technique [11] was first used by Fisher to obtain the location of the axis of elbow flexion [6].

Bottlang et al. used direct electromagnetic motion tracking to trace the passive and dynamic motion of the natural elbow joint [7]. With improving technology and silicone technology, inertial and magnetic sensors have also been employed for measuring human joints [8].

In this study, a Stewart platform (SP) based device was developed for measuring the elbow kinematics. The SP mechanism was first proposed as a flight simulator in 1965 by Stewart [9]. The Stewart platform consists of a fixed platform (base) and mobile platform (Fig 1) with six measurement sensor actuators, but instead of actuators our study used six linear potentiometers (Celesco string Pot, SPI), these potentiometers were attached to the mobile platform using cords. The forearm and the upper arm are being placed on the respective mobile and fixed platforms and firmly anchored using belts. The mobile platform consists of a metal plate that has six cords attached to it. When the forearm is moved the length of the cords change and this is registered by the sensors relative to the fixed platform. Therefore the positions of the forearm are compared relative to the upper arm. One cord-senor unit allows one degree of freedom and hence six cords measure six of them. Data given by the sensors are measured as the lengths of cords vary relative to a reference length during motion. These devices are effectively rotational potentiometers.

Another aspect of this device is its ability to measure the centre of rotation of the elbow joint during flexion. The centre of rotation moves during flexion, relative to the platform. The pattern of the centre of rotation can be measured using the SP.
MATERIALS AND METHODS

Stewart platform mechanism is a six-axis parallel mechanism. It has a fixed plate, a mobile plate and six linear potentiometers which have been mounted between the mobile plate and the fixed plate using spherical or universal joints. This configuration allows the mechanism to have three translational and three rotational motions. The data obtained from the potentiometers can be used for calculating the joint kinematics.

To start an experimental test the limb is placed in the device. It is important to stabilize the limb proximal and distal to the joint on the Stewart platform plates allowing pure joint motion to be measured. Then by moving the joint and hence the mobile plates which are connected to the potentiometers the kinematics of the joint can be measured.

The data from potentiometer will be recorded using a data acquisition device while the joint is moving. The data is then transferred to Matlab Simmechanics (Mathworks, Natick, MA, USA) to calculate the centre of rotation of the joint. This program can simulate the dynamics and kinematics of the joint.

The Stewart platform initially was calibrated by measuring the centre of rotation and angles of motion of an identical dummy joint. Then the kinematics of the elbow of a 32 year old male patient was constructed. The motion measured included flexion, extension, valgus and varus motion and was compared with his intact elbow.

The data from potentiometers of Stewart platform were used for calculating the elbow kinematics. Fig 3 illustrates the block diagram of measurement of the elbow kinematics by Stewart platform.

As shown in Fig 4, the first step is to anchor the subject’s forearm to the Stewart platform mechanism. The next step involves gathering the potentiometer data from the data acquisition device while the forearm is moving. Calculating the position of the centre of gravity of the SP using the model of SP derived from Matlab Simmechanics constitutes the third step in measurement. The Matlab Simmechanics model includes the forward dynamics and kinematics of the SP. The forward kinematics method is one of the critical phases of measurement. In parallel mechanisms such as the SP, it is extremely difficult to derive the positions of the centre of gravity from the leg lengths. Many methods have been developed for solving this problem. The most important of these is the Newton-Rhapson method, which uses an iterative solution [10]. The block diagram of a virtual Simmechanics model of SP is shown in Fig 3. The final step allows us to obtain the elbow kinematics from the position of the SP.

The six potentiometers transfer measured data from the varying lengths of the cords to the Lab View program by aid of a data acquisition device (Pico, ADC-11). The motion of the mechanism then was simulated using Matlab Simmechanics Simulation blocks to calculate three translational and three rotational positions of center point of the platform (Fig.4).

Simulation using simmechanics

Simmechanics is a block diagram modeling environment for engineering design and simulation of rigid body mechanics and their motion, using standard Newtonian dynamics of forces and torques’ [12]. In Simmechanics, it is possible to model and simulate a mechanical system by specifying bodies, by their mass properties, possible motions, kinematic constraints, and coordinate systems. The code allows the user to initiate and measure rigid body motions.

Modeleling of Stewart platform in Simmechanics

To model the Stewart platform using Simmechanics, the following stage has to be done.
1- model physical plant
2- reference trajectory generation
3- controller design
4- initialization of the plant
5- visualization of platform

Figure 4. Simulation block diagram of Stewart platform mechanism

Evaluating rotation radius
Three displacement and rotational parameters of SP are listed in Table 1.

Table 1. Three displacement and rotational parameters of SP

<table>
<thead>
<tr>
<th></th>
<th>Description</th>
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<tbody>
<tr>
<td>X</td>
<td>Translational displacement of SP through axis X</td>
</tr>
<tr>
<td>Y</td>
<td>Translational displacement of SP through axis Y</td>
</tr>
<tr>
<td>Z</td>
<td>Translational displacement of SP through axis Z</td>
</tr>
<tr>
<td>β</td>
<td>Rotational displacement of SP along axis X</td>
</tr>
<tr>
<td>α</td>
<td>Rotational displacement of SP along axis Y</td>
</tr>
</tbody>
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Assuming a small displacement with β angle (see Fig 5), the relation between displacement and the angle of motion can be given as:

\[ u^2 = x^2 + y^2 - 2r_c \cos \beta \]

In this equation \( u \) represents the total translational displacement of SP.

\[ u = \sqrt{x^2 + y^2 + z^2} \]

This value, \( u \) can be calculated from simulation. The \( r_c \) term represents the radius of rotation. Radius of Rotation \( r_c \) can be obtained by extracting \( r_c \) term from cosine expression.

\[ r_c = \sqrt{\frac{u^2}{2 - 2 \cos \beta}} \]

Equation of radius of rotation is directly related with changes of axis \( \beta \). \( r_c \) goes infinite while \( \cos \beta = 1 \). In this system the initial value of \( \beta \) is between 11 and 46 degrees, so in these expressions are acceptable for small deviations on value \( \beta \). This means these equations are valid for only valgus-varus motion.

The displacement of center of rotation (COR) is related to the joint. In living organisms the center of joint rotation cannot be determined easily because of tissue dynamics. It is possible to get information about joint laxity of the human elbow joint from the valgus-varus motion of forearm. Flexion and extension motion cannot give significant information about joint laxity because the degree of freedom the elbow allows. Valgus-varus motion is more discriminative and relates clinically to laxity. Valgus-varus motion is related with the position of SP in XY plane. As it’s shown in figure α describes the motion range. The displacement of COR in axis X can be calculated from geometric relations on triangle:

\[ C_x = -r_c \cos (\alpha) \]

Minus in this equation comes from the base plane. Because COR placed negative side of base plane on axis X.

From the same geometric relations, it is possible to find COR in axis Y and Z.

\[ C_y = r_c \sin (\alpha) \]

\[ C_z = z - r_c \sin (\beta') \]

**EXPERIMENTAL RESULTS**

The result obtained from the analysis of SP is shown following.

Fig 6 shows the COR positions in three different plans.
Figure 7. 3D view of COR of the patient’s elbows

Points of COR of two patients in 3D view are seen in Fig 7. In Fig 7, points that market with red “o” and green “+” shows the COR points of patient 1 and 2, respectively. Blue “/” and cyan “*” shows the displacement of mobile plate of the Stewart Platform Mechanism connected with the forearm of patients. Fig 8 shows the same COR points in two dimensional view.

Large values of displacement on COR points denotes a fixing problem with the forearm and Stewart Platform Mechanism in Fig 7 and Fig 8.

CONCLUSION

The Steward Platform based elbow joint measurement device is tested with basic motions of the forearm. The mechanism was tested with a patient’s two elbows and succeeded in measuring all the motions of the forearm and ascertaining the centre of rotation. Tests were executed with the help of another person to ensure that the subjects made the specified motions.

Although the accuracy of the device may be enough for lab experimental study but the device need further work to be used clinically as a diagnostic device for measurement of the joint laxity.

REFERENCE