Kinematics Analysis of the Elbow Joint; Comparison of the Kinematics of the Left and Right Elbow

Mohammad Alrashidi, Ibrahim Yildiz, Qureish Vanat, Minoo Esat, Mahmoud Chizari*

Abstract—**The aim of this study is to measure the kinematics of elbow joints using a newly developed motion tracking system, the Stewart platform (SP). The aim is to find a correlation between the trajectory of an intact joint and a joint suffering from laxity. Using the device, an in-vivo measurement of the center of rotation of the elbow joint was setup and the result of the left and right elbows were compared. It has been shown that unexpected motion of the joint such as laxity can be monitored using the device.**

***Index Terms*—kinematics, elbow joint, Stewart platform, mechanical testing**

I. 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 elbow joint motion [2], measuring elbow flexion and forearm rotation by using an electronic goniometer; and in another study they used biplanar roentgenograms [3]. Their work obtained three-dimensional kinematics of the joint. Tanaka et al. [4] used electromagnetic motion tracking data and described the first three-dimensional elbow kinematics. Lateral roentgenograms used kinematic analysis of the elbow 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 especially silicone, inertial and magnetic sensors have also been employed for analyzing human joints [8].

Manuscript received February 05, 2011; revised 05, 2011. All of the authors have no financial relationship to any private companies and organizations.

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In this study, a Stewart platform (SP) based device was developed for measuring 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 is firmly anchored to the mobile platform and the upper arm to the fixed platform 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.

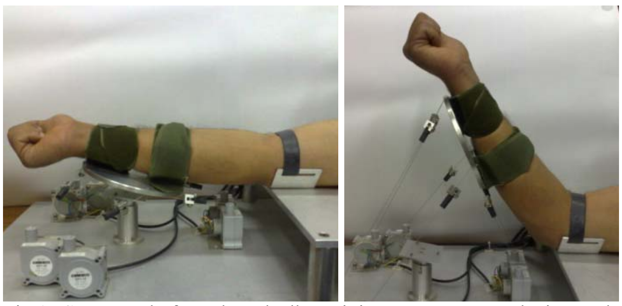

Fig.1. Stewart platform based elbow joint measurement device and arm fixation apparatus

II. MATERIAL 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.

ISBN: 978-988-19251-5-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

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 measuring flexion, extension, valgus and varus motion. This was compared with his contralateral elbow.
The data from potentiometers of Stewart platform were used for calculating the elbow kinematics. Fig 3 illustrates by block diagram measurement of elbow kinematics by Stewart platform.

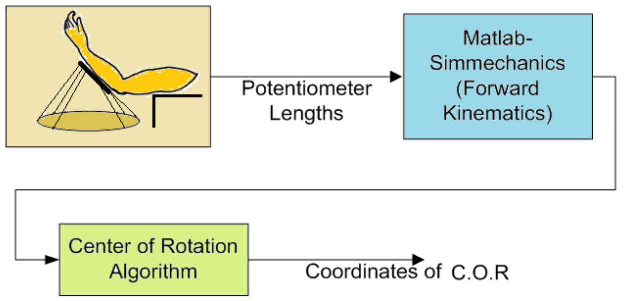

Fig 2. Measurement steps of Stewart platform.

To obtain the kinematics of a joint, initially, the 6 SP leg positions were obtained from SP sensors. Then the displacement and rotation of the links were found using the given formula. In the next step, the motion of the SP flexible plate was calculated and the center of rotation of the construct was found. Following this the kinematics of the elbow joint could be calculated using Matlab Simmechanics by employing the Newton Rhapson and Neural networks Methods.

As shown in Fig 3, 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 after a specific cycle of motion is complete. The third step in measurement is calculating the positions of the centre of rotation using the model of SP derived from Matlab Simmechanics. 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 rotation from the limb 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.

A. Evaluating rotation radius

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

Table 1. Three displacement and rotational parameters of SP

X	Translational displacement of SP through axis X
Y	Translational displacement of SP through axis Y
Z	Translational displacement of SP through axis Z
γ	Rotational displacement of SP along axis X
β	Rotational displacement of SP along axis Y
α	Rotational displacement of SP along axis Z

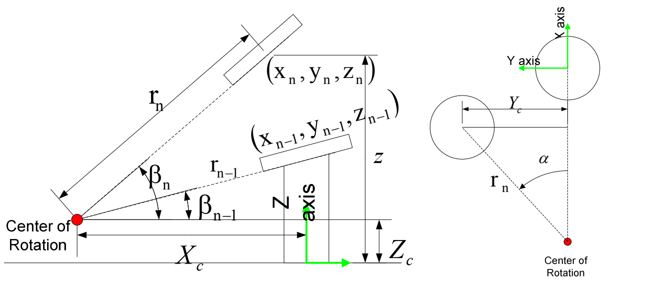

Fig 3. Side view of experimental setup (left); and the displacement of center of rotation during valgus and varus motion on XY plane (right)

In the side view of experimental setup (Fig 5), subscript "n" illustrates the n'th position of mobile plate of SP and also subscript "n-1" shows the previous position of SP. Assuming a displacement with β angle (see Fig 5), the relation between displacement and the angle of motion can be given as:

$$r_n \sin(\beta_n) = z_n - Z_c$$
$$r_{n-1} \sin(\beta_{n-1}) = z_{n-1} - Z_c$$
$$r_n \cos(\beta_n) = x_n - X_c$$
$$r_{n-1} \cos(\beta_{n-1}) = x_{n-1} - X_c$$

In this equation system there are 4 unknown variables (r_n, r_{n-1}, X_c, Z_c) and 4 equations. From these systems of equations radius of rotation can be calculated.

$$r_n = \frac{\sin(\beta_{n-1})(x_n - x_{n-1}) + \cos(\beta_{n-1})(z_{n-1} - z_n)}{\cos(\beta_n)\sin(\beta_{n-1}) - \sin(\beta_n)\cos(\beta_{n-1})}$$

ISBN: 978-988-19251-5-2
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

The r_c term represents the radius of rotation.

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 e.g. mobile tissues surrounding joints such as muscle and fat having their own movement characteristics affecting pure measurement of joint motion. To correct for this potential error the contralateral ‘intact’ side is also measured thus eliminating the soft tissue involvement.
Clinically this is particularly true in valgus-varus motion as it is more discriminative when relating to clinical laxity. However significant information cannot be obtained in flexion extension due to the limited degree of freedom the joint affords in this motion cycle.
Valgus-varus motion is related to the position of SP in XY plane. As it’s shown in Fig 5, *α* describes the motion range. The displacement of CoR in axis X can be calculated from geometric relations on triangle:

$$X_c = x_n - r_n \cos(\beta_n)$$

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

$$Y_c = y_n - r_n \sin(\alpha_n)$$

$$Z_c = z_n - r_n \sin(\beta_n)$$

III. RESULTS AND DISCUSION

To find out reliability of the Stewart Mechanism to measure different case, we used 3 different cases with the left hand and right hand. The result of measurement of a typical examination on both elbow joints of three young male ages between 30 to 36 years old is shown in Fig 4. As it is seen in Fig 4, the C.o.R of the right and left elbow joints have been drawn in X, Y, Z planes against the angle of rotation. The results show that the C.o.R for the right and left elbows are different. However there is no unexpected motion in their trajectory patterns in each plane and so it can be considered an intact joint with no laxity.
According to the Fig 4 graphs, although there are clear differences between the curves of C.o.R for these 3 left hand cases, the trend of the curves are near each other with slightly offset in the results. The offset in the position of the results is not important as it only shows the position of the centre of rotation to a specific reference and this position could be different even if the test for one hand repeats two times in the mechanism.

A Stewart Platform based elbow joint measurement device was tested using the motion at the elbow joint by extending and flexing the forearm. The device was used to test a number of healthy volunteers and successfully measured a full range of motion at the elbow giving data on the centre of rotation.
Although, tracking the motion of a joint using SP system is not new but its application and method of measurement on the elbow joint is novel. The measurement method is simple and can be stopped or repeated at any time. It can be used as an additional tool to examine the joint laxity.

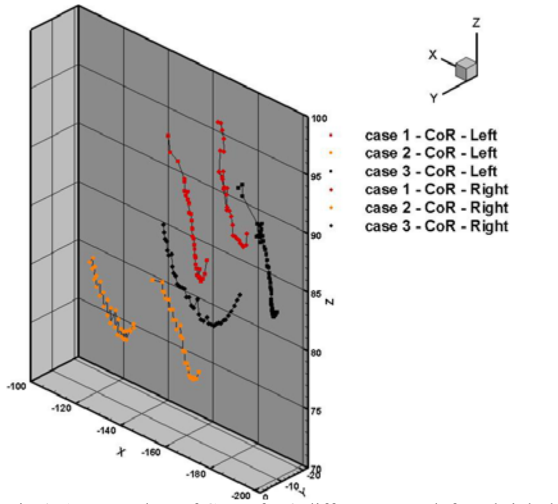

Fig 4. Average data of C.o.R for 3 different cases left and right hand

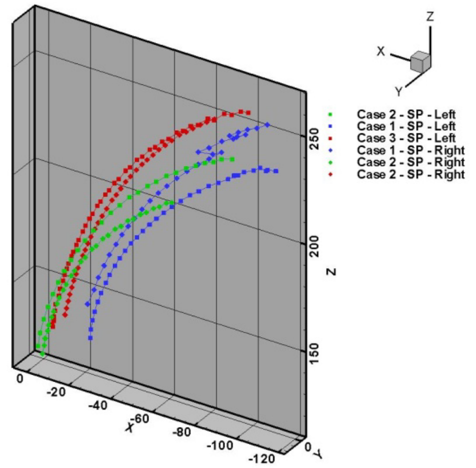

Fig 5. Average data of SP for 3 different cases left and right hand

Calibration was performed on the SP system to measure possible errors on the device and to identify whether these errors were random or constant. Constant errors were found and a factor was applied to the calculation method to reduce their effect. Random errors also were examined. Although random errors were small they had the potential to affect the results. However this did not limit the application of the device to find joint laxity but does highlight the need to improve accuracy.
It was challenging to fix the arm and forearm into the device. The potential for error was due to mobility of the soft tissues. This potential error has to consider when arriving at conclusion from the data. Although special clamps were used to fix the limb onto improvements still had to be made. One way of reducing the error was using both the test subject's limbs, assuming both are similar with regards to soft-tissue proportions. This could be considered an internal control.
This is important because the center of rotation of the joint changes due to the soft tissue envelope around the joint. The device traces the center of the joint rotation in each incremental phase of motion to plot a trajectory for the center of the joint during a normal joint motion.
This device has the potential to diagnose a lax joint if used in a clinical setting. This could determine whether or not to proceed with surgery to correct laxity in a symptomatic patient.

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IV. CONCLUSIONS AND FUTURE WORKS

In this biomechanical study we used a Stewart platform to measure the kinematics of elbow joints to find correlations between the trajectory of an intact joint and a lax joint. It is suggested by comparing the pattern of motion of both elbow joints in a patient it is possible to recognize the lax of the joint.

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