INTRODUCTION

Since the motion of wrist is almost pure rotation, spherical coordinate system is a compatible reference frame for analyzing the motion of wrist. Kinematically, human wrist can be modeled by 3DOF (FE, RUD, PS) manipulator with 2DOF (FE, RUD) in universal-like joint of wrist and additional DOF (PS) which comes from forearm[1]. Dynamically, it is shown that passive wrist stiffness is dominant dynamic of wrist [1] and depends nonlinearly on the position of wrist [2]. The present study shows that similar to passive stiffness, level of wrist noise depends on the position as well. For modeling the noise of wrist, we have studied the variation of Axis Of Rotation (AOR). Behavior of AOR not only depends on noise but also the biomechanical properties of wrist [3]. The results of experiment imply that fast changes of AOR is most probably because of internal noise (in actuation and sensing) and systematic patterns produced intentionally according to the dynamic of task and wrist.

METHODS

In this study, new approach has been followed for analyzing the wrist motion by adding a fixed link to the multi DOF joint. In fact, the new manipulator, let us call it wrist manipulator has a spherical-like joint in the origin of spherical coordinate system and a link which connects the origin to the surface of sphere with the radius of the length of link. The Jacobian matrix of new-defined manipulator can be easily obtained by finding the relation between rotational velocity at joint and translational velocity on the surface of sphere. The position of tip point of wrist manipulator can be written in vector form as

\[ \vec{L} = L_x \hat{i} + L_y \hat{j} + L_z \hat{k} \]  

(1)

The rotational velocity of link can be written in vector form as well. The translational velocity of tip point can be obtained by cross product of rotational and position vectors.

\[ \vec{V} = \omega \times \vec{L} = (\omega_i L_z - \omega_z L_i) \hat{i} + (\omega_j L_z - \omega_z L_j) \hat{j} + (\omega_k L_z - \omega_z L_k) \hat{k} \]  

(2)

By writing in matrix form and comparing with \( \vec{V} = J \Theta \), we obtain the Jacobian matrix of this manipulator. By finding the projection of displacement vector in each axis we obtain the matrix with respect to angles.

\[
\begin{bmatrix}
L_x = L \cos(\alpha) \\
L_y = L \cos(\beta) \\
L_z = L \cos(\gamma)
\end{bmatrix} \Rightarrow
J = \begin{bmatrix}
0 & L \cos(\gamma) & -L \cos(\beta) \\
-L \cos(\gamma) & 0 & L \cos(\alpha) \\
L \cos(\beta) & -L \cos(\alpha) & 0
\end{bmatrix}
\]  

(3)

The Jacobian matrix of this manipulator is skew symmetric matrix and its determinant is zero. In fact, since we can show any vector in spherical coordinate system with just two angles (Azimuth and Elevation) in comparison with three angles of wrist in FE, RUD and PS directions, then it is expectable to have Jacobian matrix which is not invertible. Since we do not have an access to wrist robot [4] for measuring the angles of wrist and at the same time the Jacobian is not invertible, we had to capture the motion of tip point of wrist manipulator and utilize AOR notion for our analysis. In addition, AOR technique magnifies the deviations at wrist motion and makes it possible to capture the small and sometimes hidden dynamic of wrist. For doing so, we used following experiment with Omni Haptic device. We asked subjects to track a pre-determined circle (10 cm diameter) on space with two different positions for 4 times with just wrist motion. Figure 1 shows the connection of human wrist and pen of Omni haptic device. The link of wrist manipulator is defined from the location of wrist to the tip point of Omni pen which is shown by Orange vector.
RESULTS AND DISCUSSION

Axis of rotation of a perfect circle is a fixed line, however when human tries to produce a circle because of noisy sensory inputs and motor commands and biomechanical properties of wrist it will not be a perfect circle. Producing a perfect circle even for a skillful person may not be possible. It is important to note that producing a circle can be done in two different ways; drawing a circle (mostly engaged with internal model of this task in nervous system) and tracking a circle (mostly engaged with internal optimal control system). The distribution of axis of rotation is a good criterion for measuring a performance of operator in producing circular motions. It is obvious that producing circular motion is just a primitive example for generation versatile kinds of motions like writing a letter and doing deburring with so many curvature motions. The probabilistic model of producing circular motion reveals the performance and impairment of a subject. Figure 2 shows the distribution of elevation and azimuth angles of AOR for two different positions of wrist produced four times for one subject. It denotes that AOR is more noisy for second position in Azimuth direction.

As it is shown in Figures 3 and 4 (left ones), the special region of ROM are more noisy than other regions and this pattern is almost same for a same position and different cycles. It shows that wrist noise is position- depended signal. On the other hand, there are some sharp changes of elevation angles (right ones) which are same again for different cycles. The systematic pattern of behavior of AOR reveals that noise is not the only source of this pattern. The biomechanical properties of wrist and the dynamic of task may determine the shape of those patterns. In this study we showed that the variance of noise is changing during task; moreover; the unique behavior of elevation and azimuth angles of AOR denotes that there should be a systematic pattern for this task. However the mathematical and biomechanical reasons behind this phenomenon are not represented here. The advantage of this study is that it will help us to create a comprehensive map of wrist noise in entire range of motion.

REFERENCES

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