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Stiffness measurement of the gleno-humeral joint

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Abstract

Shoulder pain in hemiplegia following stroke is common, and has been associated with subluxation in the gleno-humeral joint. It is hypothesised in the current study that dynamic stability is a more useful measure than subluxation when predicting pain, which will help in the optimisation of treatment options in this group (including neuromuscular stimulation). A system identification technique is used to characterise the dynamic properties of the glenohumeral joint. Random displacement perturbations are applied to the arm, and the force response is measured. Results show that the mechanical properties of the system could be reliably identified using this technique.

1. INTRODUCTION

Stroke is the leading cause of activity limitation among older adults in the United States. More than 700,000 strokes occur each year [2], with a prevalence of approximately 4 million (AHA, 1997). A common complication of stroke is hemiplegic shoulder pain with reported prevalence ranging between 34% and 84% [6][3].

A recent study [1] showed that the presence of shoulder subluxation (displacement of the humeral head relative to the glenoid) and limited range of motion are associated with hemiplegic shoulder pain, but the aetiology is poorly understood. Neuro-muscular electrical stimulation (NMES) is the only treatment option that has been shown to be effective in randomised controlled trials, although in a number of studies, it was not found to be effective [7][8].

Subluxation is a simple measure of instability though, and fails to capture the dynamic, three-dimensional nature of stability. It is hypothesised that dynamic stability is a better predictor of pain than subluxation, and will lead to further elucidation of the relationship between pain and instability.

The overall goal of this research is to identify the mechanical and neuromuscular changes in the hemiplegic shoulder following stroke and their relationship to the development of pain. The objective of this study was to develop a method for the measurement of the dynamic stiffness of the gleno-humeral joint, as an indicator of gleno-humeral stability. This correlation of this measure with clinical measures such as pain will allow the improvement of treatment options for this group.

Similar methods have been used previously to identify the dynamic characteristics of the whole arm in able-bodied and spinal-cord-injured subjects [5][4].

2. METHODS

Stochastic displacement perturbations in the range 0-6Hz, 0-2cm, were applied to the arm using a manipulator (Figure 1) during a constant force task, while end-point forces and displacements were recorded. The subject's arm was firmly attached to the manipulator by means of a cast from the mid-humerus level to the wrist, with the elbow in 90°. This ensured that the displacements imposed on the system would result in movements at the shoulder, and not movement of the manipulator with respect to the arm.

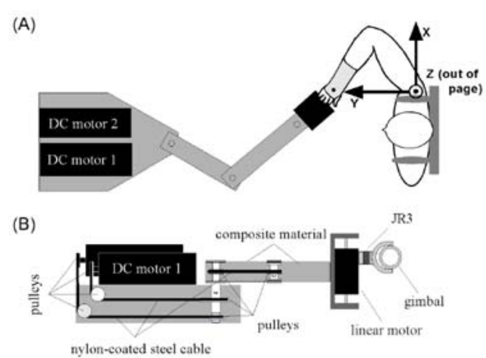

Figure 1 Schematic representation of the 3-D manipulator. Two rotary motors provide motion in the horizonal plane, and a linear motor provides the motion in the vertical direction. The manipulator allows the imposition of displacement perturbations on the arm.

The subject was asked to complete a constant-input task, such as pushing in a certain direction or maintaining a zero net force on the endpoint, for a 30 second period while displacement perturbations were imposed on the humerus. This method differs from previous work in that other studies have concentrated on measuring whole arm stiffness, and have therefore not fixed the elbow. This method is designed specifically to induce movements at the gleno-humeral joint.

System identification techniques were used to quantify dynamic stiffness of the shoulder, with humeral end-point motion as input and end-point force as output for the system. The system was modelled as a set of single-input single-output 2nd order systems [5] represented by the H-blocks in Equation 1 and shown in Figure 2.

$$\begin{bmatrix} F_x(f) \\ F_y(f) \\ F_z(f) \end{bmatrix} = \begin{bmatrix} H_{xx}(f) & H_{xy}(f) & H_{xz}(f) \\ H_{yx}(f) & H_{yy}(f) & H_{yz}(f) \\ H_{zx}(f) & H_{zy}(f) & H_{zz}(f) \end{bmatrix} \begin{bmatrix} X_x(f) \\ X_y(f) \\ X_z(f) \end{bmatrix} \quad (1)$$

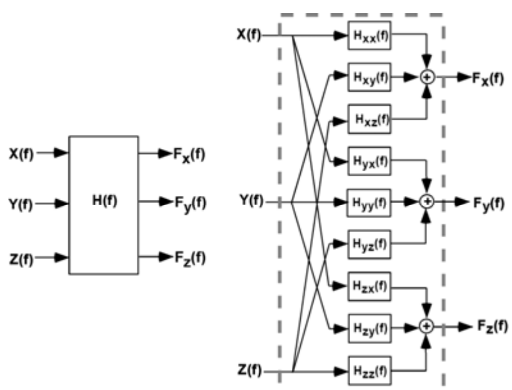

Figure 2 Representation of a 3-input 3-output stiffness system. X, Y and Z are endpoint displacements and Fx, Fy and Fz are endpoint forces. The 9 different H-blocks are the stiffness properties between each displacement.

3. RESULTS

The preliminary data presented here are based on a 2-D analysis, though ultimately the study will be a full three-dimensional analysis. Figure 3 shows the magnitudes of the transfer functions for the principal directions (leading diagonal) as well as the interaction between directions (off-diagonal). Displacement of the endpoint (elbow) in the medio-lateral direction,

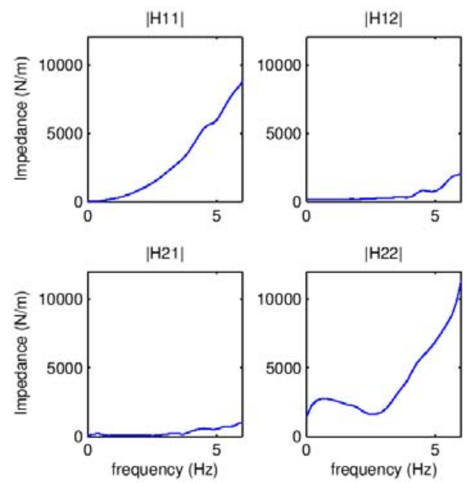

Figure 4 Dynamic stiffness of the shoulder during a 10N vertical (up) push task. Higher stiffness is seen in the anteroposterior direction (H11) than mediolaterally (H22).

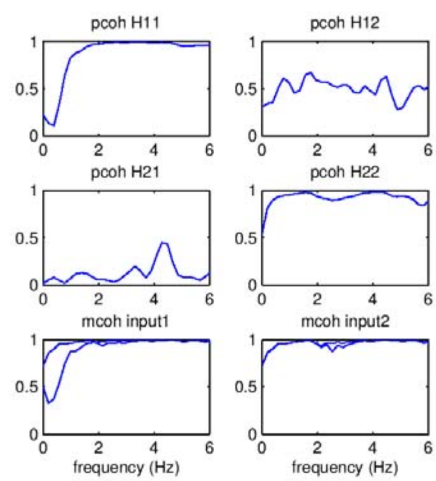

Figure 3 Partial and multiple coherences for the system identification. Partial coherences approach 1 in the principal directions (H11 and H22), but are much lower in the coupling directions (H12 and H21).

which was approximately perpendicular to the long axis of the humerus, resulted in rotation of the gleno-humeral joint, and displacement in the antero-posterior direction, in line with the axis of the humerus, resulted in translation at the joint.

Partial and multiple coherence plots for the identification are shown in Figure 4. The values of pcoh approach one for the principal directions, but are much lower for the coupling directions.

4. DISCUSSION AND CONCLUSIONS

Medio-lateral displacement of the endpoint induces rotation in the glenohumeral joint, whereas antero-posterior displacement of the endpoint (in line with the humerus) induces displacement in the GH joint. This is reflected in the much higher stiffness (impedance at 0Hz) of H22 than of H11, and confirms the effectiveness of the cast in transferring load to the humerus.

The excellent partial coherences pcoh H11 and pcoh H22 demonstrate that the response of the system in those directions could be very well characterised by the identified frequency response functions. The much lower coherences for the coupling components (pcoh H12 and pcoh H21) are a result of very small couplings between the medio-lateral and antero-posterior directions.

The method appears to be appropriate for the measurement of dynamic gleno-humeral stiffness, with the mechanical properties of the system being reliably identified. Further investigation will establish its repeatability and validity, as well as its ability to detect changes in the neuromuscular system following stroke.

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