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To Design a Small Pneumatic Actuator Driven Parallel Link Mechanism for Shoulder Prostheses for Daily Living Use

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1. Introduction

Only in Japan, there are about 82,000 upper limb amputees (Ministry of Health, Labour and Welfare, 2005). Using upper limb prostheses could restore the function for them, thus improve significantly the quality of their activities of daily living [ADL]. Compared with below-elbow prostheses, shoulder prostheses are left behind in their development, due to high degrees of freedom [DOF] required, which demands a large number of actuators, thus denotes a large size and a heavy weight, and complicated control mechanism. Recently, there is a certain body of research on developing robotic devices that could be used as prostheses for shoulder amputees (Jacobson et al., 1982; Motion Control, Inc., 2006-2011; The Johns Hopkins University Applied Physics Laboratory [APL], 2011; Troncossi et al., 2005, 2009a, 2009b). These research efforts have led to artificial prostheses with high functionality and performance. For example, the prosthetic arm of Defense Advanced Research Projects Agency and APL, has 25 DOFs, individual finger movements, dexterity that approaches that of the human limb, natural control, sensory feedback, and a number of small wireless devices that can be surgically implanted (or injected) to allow access to intramuscular signals (APL, 2011). The Utah Arm 3, a modification of the previous Utah Arm that has been the premier myoelectric arm for above elbow amputees, has two microcontrollers that are programmed for the hand and elbow, accordingly, allowing separate inputs and hence simultaneous control of both, and that is, the wearer can operate the hand and elbow concurrently for natural function (Jacobson et al., 1982; Motion Control, Inc., 2006-2011). The hybrid electric prosthesis for single arm amputee of Tokyo Denki University possesses a ball joint of 3 DOFs in humeral articulation. Patient operates the prosthesis to optional point by pressing a switch with the other healthy limb to free the joint, and releases to fix and hold the prosthetic arm stably (Nasu et al., 2001). Moreover, the electromechanical shoulder articulation with 2 DOFs for upper-limb prosthesis that has two actuated joints embedded harmonic drives, an inverted slider crank mechanism, and ball screw, has been developed (Troncossi et al., 2005, 2009a, 2009b).

These prostheses have the following characteristics: they are more or less anthropomorphic, basically supported by metal frames or parts, driven by electric motors, therefore, many of them seem to be not suitable for the daily living use: they are not light weight, not convenient, with a bad portability, and lack of backdrivability which could contribute to the safety use in daily living.
Using pneumatic actuators (Festo AG & Co. KG, 2002-2008; Folgheraiter & Gini, 2005), some researchers have developed sophisticated manipulators having structure similar to human upper limb. Employing pneumatic actuators that could naturally realize backdrivability, ensures safety against collisions or contact between the prosthetic shoulder and its environments around. In the Airic's arm (Festo AG & Co. KG, 2000-2008), 30 artificial muscles were used to move the artificial bone structure comprising the ulna, radius, the metacarpal bones and the bones of the fingers, as well as the shoulder joint and the shoulder blade. The MaximumOne, a robot arm of Artificial Intelligence and Robotics Laboratory, Politecnico di Milano, consists of two joints with 4 DOFs in all. The shoulder is made up of a ball joint with 3 DOFs and driven by five actuators, and the elbow is a revolute joint with 1 DOF and driven by two actuators (Folgheraiter & Gini, 2005). However, the manipulators are basically not for prosthetic use, moreover, they are not portable, especially due to the big air compressor.

This study aims to develop a lightweight shoulder prosthesis that could be easily fitted to and carried by amputees, therefore a convenient one. This chapter presents kinematical analysis, procedure for finding optimal configurations for the prosthetic arm, and verification of the design concepts.

2. Design concepts

A shoulder prosthesis for daily living use should be light-weight, portable, and safe. Consideration to design such a shoulder prosthesis is described as follows.

1. Using small pneumatic actuators driven by small portable air compressor for weight saving and portability. To meet portability and light-weight requirements, small actuators and compressors are musts for shoulder prostheses. The pneumatic actuators Sik-t, Sik-t Power-Type (Squse Inc.: 1g, 20N; 3g, 130N), air compressors MP-2-C (Squse Inc.: 180g, 0.4 MPa) are products developed recently for robotic application with light-weight and good portability. In this research, these products were employed as actuators and their air sources. The purpose of this research is to design shoulder prostheses with optimal spatial functionality using these actuators.

2. Employing a parallel link mechanism to enable high rigidity and high torque output. The natural viscoelasticity of pneumatic actuators could contribute to backdrivability, and safety of shoulder prostheses, however, it also affects the payload of the system. Moreover, since small actuators have a limited tensile force, a structure that could exert high torque output is preferable. That is why a parallel link mechanism that could improve structural rigidity was employed. However, the parallel link structure usually has a limited stretch along axial direction. The working space of the prostheses should be adjusted to fit individual users’ expected frequently accessed area [EFAA]. To the best of our knowledge, there are no investigation results reported on how to match working space of end-effector to EFAA of individual users’ hand. This is the main objective of this study.

3. Using a rubber backbone for the parallel link mechanism to enable trade-off between working space and payloads. Since, the parallel link structure usually has a limited stretch along axial direction. A flexible backbone for the parallel link could give more possibility to deal with the trade-off between payloads and working space, however, this raises one more design variable, which should also be carefully investigated in the design process. This is an on-going research theme, and will be addressed in other papers.
4. Designing a special backpack that could contain the shoulder prostheses and all accessories, and could be worn by the amputee user himself with minimal effort. This needs the shoulder prosthesis be foldable, and the backpack be designed for conveniently getting the shoulder prosthesis in and out. This will be approached in the next stage and addressed in other papers. The ultimate goal of this study is to build a shoulder prosthesis that could be used in daily living by shoulder amputees. The purpose of this paper is to describe the structure of the prosthesis, and approach to find optimal configurations based on the aforementioned design consideration. Fig. 1 shows an illustration of the shoulder prosthetic system, which is drafted with computer aided design [CAD] software SolidWorks (Dassault Systèmes SolidWorks Corp.) and human body model from HumanWorks software (zetec, Ltd.)

The remainder of this chapter is organized as follows. At first, in section 3, the basic structure of the prosthesis was described and several formulae for kinematics and statics of it were derived for further analysis. After that, the way to achieve the spatial accessibility and manipulability was explained in section 4. Then several experimental results concerning the design of the prosthesis were shown with discussion. Following that, a conclusion was given based on the results and discussion.

Fig. 1. The shoulder prosthetic system.

3. Kinematics and statics

To decide the physical dimension of the shoulder prosthesis, both the kinematics, statics of the prosthesis and the spatial configuration, expected frequently accessed area [EFAA] of users’ hand should be considered. In this section, the kinematics and statics of the proposed shoulder prosthesis were derived for further analysis. Several estimative indexes were also defined to compare different potential solutions, thus to decide physical dimensions (configuration) of the shoulder prosthesis. As described before, only the arm structure was modelled and analyzed, whereas the prosthesis with hand, the backpack, and the connection between arm structure and backpack were left for further studies.
3.1 Arm structure
The details of the arm structure (in the following explanation, denoted as the Arm) are shown in Fig. 2. The Arm is composed of three segments. Segment 1 links two disks called the Base 1 and the Platform 1 with the Backbone 1 and three pneumatic actuators, placed equiangularly with respect to the center of the Base 1. The Backbone 1 is fixed to the center of the Base 1, and connected to the center of the Platform 1 with two passive revolute joints. To simplify the analysis, the Backbone 1 was assumed as a compression spring that can only move along longitudinal direction, but not as a rubber rod as described in the design concept section. By assembling Base 1 and Platform 1 with a compressed Backbone 1, actuators and wires that connect the pneumatic actuators with two disks are constantly loaded. This allows the Platform 1 to move along the longitudinal direction of the Backbone 1, turn around the joint of Platform 1 and Backbone 1, as a result of length changes of the three actuators. The Platform 1 disk of Segment 1 is also used as the Base 2 disk of the Segment 2, which has a similar structure with the Segment 1, but with a different length. Segment 3 contains only a rigid rod (Rod) fixed to the center of outside the Platform 2, i.e. the Base 3 of the Segment 3. For the convenience of description, let $h_1$, $h_2$ and $l_R$ be the initial length of the Backbone 1, 2 and Rod respectively.

Fig. 2. The structure of the Arm.

3.2 Kinematics
In order to analyze the behavior of end-effector and working space of the Arm, forward and inverse kinematics model of the parallel link mechanism were derived. The coordinate system of the Arm is shown in Fig. 3. Without loss of the generality, the thicknesses of all disks, and the shaft diameters of Backbone 1, 2, Rod were set to 0. The global
coordinate system $O_{B1}$-XYZ is located at the center of the Base 1, with the Z-axis directed along the Backbone 1. The contact points of three pneumatic actuators to Base 1 ($B_{11}, B_{12}, B_{13}$) were aligned equiangularly along the peripheral of a circle with a radius $r_B$, and $B_{11}$ is on the X-axis.

The local coordinate system $O_{P1}$-x$_{P1}$y$_{P1}$z$_{P1}$ locates at the center of disk Platform 1, $h_1$ away from $O_{B1}$ along the Z-axis. The contact points of pneumatic actuators to Platform 1 ($P_{11}, P_{12}, P_{13}$) are on radius $r_P$. In turn, the contact points of three pneumatic actuators to Base 2 ($B_{21}, B_{22}, B_{23}$) are equiangularly set on circumference of a circle, radius $r_B$, and $B_{21}$ is on the x$_{P1}$-axis. The local coordinate system $O_{P2}$-x$_{P2}$y$_{P2}$z$_{P2}$ is set at the center of Platform 2, and the distance from $O_{P1}$ is $h_2$. The contact points ($P_{21}, P_{22}, P_{23}$) are aligned equiangularly along the peripheral of a circle with a radius $r_P$, and $P_{21}$ is on the x$_{P2}$-axis.

Finally, the Rod of length $l_R$ is fixed up at $O_{P2}$ along the z$_{P2}$-axis.

Suppose the actuators are activated, and their lengths change (expressed discretely: $l_i$ gets to $l'_i$, $i = 1, ..., 6$). Therefore, $h_1$ and $h_2$ are converted to $h'_1$ and $h'_2$, two passive joints (Joint 1) of Platform 1 and the one (Joint 2) of Platform 2 rotate by $\alpha, \beta, \gamma, \sigma$ (see Fig. 2, 3), respectively.

Fig. 3. Geometry of the parallel link arm.

At first, the position of $O_{P1}$, $P_{1i}, P_{1i}'$ ($i = 1, 2, 3$) and the rotation matrix $R_1$ of Joint 1 in $O_{P1}$-x$_{P1}$y$_{P1}$z$_{P1}$, i.e. $^{p1}O_{P1}, ^{p1}P_{1i}, ^{p1}P_{1i}'$ and $^{p1}R_1$ can be presented as follows:
\[ p_i \mathbf{O}_{P_i} : (0, 0, 0), \quad p_i \mathbf{P}_{1i} : (r_p, 0, 0), \quad p_i \mathbf{P}_{12} : (-\frac{1}{2} r_p, \frac{\sqrt{3}}{2} r_p, 0), \quad p_i \mathbf{P}_{13} : (\frac{1}{2} r_p, -\frac{\sqrt{3}}{2} r_p, 0) \] 

(1)

\[ p_i \mathbf{R}_i = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & -\sin \alpha \\ 0 & \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \cos \beta & 0 \\ 0 & 1 \\ -\sin \beta & 0 \end{pmatrix} \begin{pmatrix} \cos \beta & 0 \\ 0 & \sin \alpha \sin \beta & \cos \alpha - \sin \alpha \cos \beta \\ -\cos \alpha \sin \beta & \sin \alpha & \cos \alpha \cos \beta \end{pmatrix} \] 

(2)

And,

\[ p_i \mathbf{P}_{1i}' = p_i \mathbf{R}_i p_i \mathbf{P}_i \quad (i = 1, 2, 3) \] 

(3)

Therefore, the coordinate of each element of \( p_i \mathbf{P}_{1i}' \) is:

\[ p_i \mathbf{P}_{11}' : (r_p \cos \beta, r_p \sin \alpha \sin \beta, -r_p \cos \alpha \sin \beta) \]

\[ p_i \mathbf{P}_{12}' : (-\frac{1}{2} r_p \cos \beta, -\frac{1}{2} r_p \sin \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \cos \alpha, \frac{1}{2} r_p \cos \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \sin \alpha) \] 

(4)

\[ p_i \mathbf{P}_{13}' : (-\frac{1}{2} r_p \cos \beta, -\frac{1}{2} r_p \sin \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \cos \alpha, \frac{1}{2} r_p \cos \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \sin \alpha) \]

Next, \( p_i \mathbf{P}_{1i}' \), \( B_{1i}' \) in \( O_{B1}-XYZ \), i.e. \( B_{1i}' \) and \( B_{1i}' \) can be defined as:

\[ B_{1i} : (r_B, 0, 0), \quad B_{12} : (-\frac{1}{2} r_{B}, \frac{\sqrt{3}}{2} r_B, 0), \quad B_{13} : (-\frac{1}{2} r_{B}, -\frac{\sqrt{3}}{2} r_B, 0) \] 

(5)

\[ B_{1i}' = p_i \mathbf{P}_{1i}' + (0, 0, h_i) \] 

(6)

So, each element of \( B_{1i}' \) can be expressed as:

\[ B_{1i} : (r_p \cos \beta, r_p \sin \alpha \sin \beta, -r_p \cos \alpha \sin \beta + h_i) \]

\[ B_{12} : (-\frac{1}{2} r_p \cos \beta, -\frac{1}{2} r_p \sin \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \cos \alpha, \frac{1}{2} r_p \cos \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \sin \alpha + h_i) \] 

(7)

\[ B_{13} : (-\frac{1}{2} r_p \cos \beta, -\frac{1}{2} r_p \sin \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \cos \alpha, \frac{1}{2} r_p \cos \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \sin \alpha + h_i) \]

Accordingly, the length of each actuator can be defined:

\[ l_i' = B_{1i}' B_{1i} \quad (i = 1, 2, 3) \] 

(8)

By Equation (5), (7) and (8), the equations describing the relation between the lengths of pneumatic actuators, wires attached in Segment 1, Backbone 1, and the angles of two revolute joints can be defined as follows:

\[ (l_i')^2 = \left( r_p \cos \beta - r_B \right)^2 + \left( r_p \sin \alpha \sin \beta \right)^2 + \left( -r_p \cos \alpha \sin \beta + h_1 \right)^2 \]
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\[
(l_2)^2 = \left( -\frac{1}{2} r_p \cos \beta + \frac{1}{2} r_b \right)^2 + \left( -\frac{1}{2} r_p \sin \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \cos \alpha - \frac{\sqrt{3}}{2} r_b \right)^2
\]
\[
+ \left( \frac{1}{2} r_p \cos \alpha \sin \beta + \frac{\sqrt{3}}{2} r_p \sin \alpha + h_1 \right)^2
\]

\[
(l_3)^2 = \left( -\frac{1}{2} r_p \cos \beta + \frac{1}{2} r_b \right)^2 + \left( -\frac{1}{2} r_p \sin \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \cos \alpha + \frac{\sqrt{3}}{2} r_b \right)^2
\]
\[
+ \left( \frac{1}{2} r_p \cos \alpha \sin \beta - \frac{\sqrt{3}}{2} r_p \sin \alpha + h_1 \right)^2
\]

Equation (9) is a simultaneous equation with three unknown variables, \(\alpha, \beta, h_1\). In the case that the lengths \(l_1', l_2', l_3'\) are given, it is possible to calculate \(\alpha, \beta, h_1\) by using the Newton method (Ku, 1999; Merlet, 1993; Press et al., 1992). Similarly, for the Segment 2 (i.e. in \(O_{p1-xp}yp_{p1}z_{p1}\)), the following equation can be derived. In the case that the length \(l_4', l_5', l_6'\) are given, it is possible to calculate \(\gamma, \sigma, h_2\).

\[
(l_4)^2 = \left( r_p \cos \sigma - r_b \right)^2 + \left( r_p \sin \gamma \sin \sigma \right)^2 + \left( -r_p \cos \gamma \sin \sigma + h_1 \right)^2
\]

\[
(l_5)^2 = \left( -\frac{1}{2} r_p \cos \sigma + \frac{1}{2} r_b \right)^2 + \left( -\frac{1}{2} r_p \sin \gamma \sin \sigma - \frac{\sqrt{3}}{2} r_p \cos \gamma + \frac{\sqrt{3}}{2} r_b \right)^2
\]
\[
+ \left( \frac{1}{2} r_p \cos \gamma \sin \sigma + \frac{\sqrt{3}}{2} r_p \sin \gamma + h_1 \right)^2
\]

\[
(l_6)^2 = \left( -\frac{1}{2} r_p \cos \sigma + \frac{1}{2} r_b \right)^2 + \left( -\frac{1}{2} r_p \sin \gamma \sin \sigma - \frac{\sqrt{3}}{2} r_p \cos \gamma - \frac{\sqrt{3}}{2} r_b \right)^2
\]
\[
+ \left( \frac{1}{2} r_p \cos \gamma \sin \sigma - \frac{\sqrt{3}}{2} r_p \sin \gamma + h_1 \right)^2
\]

The position of the Rod end \(P_{RE'}\) in \(O_{p2-xp2}yp_{p2}z_{p2}\), i.e. \(p2P_{RE'}\) can be defined as:

\[
p2P_{RE'} = (0, 0, l_r)^T
\]

Let \(x, y, z\) be the coordinate of \(b1P_{RE'}\), then end position of the Rod, \(x, y, z\) in \(O_{b1}-XYZ\) can be described as:

\[
(x \ y \ z) = p1R(p2R(p2P_{RE'} + p1O_{p2}) + b1O_{p1})
\]

\[
\begin{bmatrix}
  x \\
  y \\
  z
\end{bmatrix} =
\begin{bmatrix}
  \cos \beta & 0 & \sin \beta \\
  \sin \alpha \sin \beta & \cos \alpha & -\sin \alpha \cos \beta \\
  -\cos \alpha \sin \beta & \sin \beta & \cos \alpha \cos \beta
\end{bmatrix}
\begin{bmatrix}
  \cos \sigma & 0 & \sin \sigma \\
  \sin \gamma \sin \sigma & \cos \gamma \cos \sigma & -\sin \gamma \sin \cos \sigma \\
  -\cos \gamma \sin \sigma & \sin \gamma \cos \sigma & \cos \gamma \cos \sigma
\end{bmatrix}
\begin{bmatrix}
  0 \\
  0 \\
  l_r
\end{bmatrix}
+ \begin{bmatrix}
  0 \\
  0 \\
  h_1
\end{bmatrix}
\]

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3.3 Jacobian matrix

In order to evaluate the motion characteristics of the Arm, it is necessary to develop the Jacobian matrix of the Arm structure.

As \( l'(i=1, \ldots, 6), \alpha, \beta, h'_t, \gamma, \sigma \) and \( h'_t \) can be taken as functions of time \( t \), noticing \( l', \dot{x}, \dot{y}, \dot{z} \) are functions of \( \alpha, \beta, h'_t, \gamma, \sigma, h'_t \), the Equation (9), (10), (12) can be differentiated with respect to \( t \), to get the following equations. The \( A, B, C \) are the matrices with element \( a_{ij}, b_{ij} (i,j=1,2,3) \), \( c_{ij} (i=1,2,3, j=1, \ldots, 6) \), respectively.

\[
\begin{pmatrix}
\dot{l}'_1 \\
\dot{l}'_2 \\
\dot{l}'_3
\end{pmatrix}
= A
\begin{pmatrix}
\alpha \\
\beta \\
h'_t
\end{pmatrix}
= B
\begin{pmatrix}
\gamma \\
\sigma \\
h'_t
\end{pmatrix}
\]

(13)

\[
\begin{pmatrix}
x \\
y \\
z
\end{pmatrix}
= C
\begin{pmatrix}
\alpha \\
\beta \\
h'_t
\end{pmatrix}
\]

(14)

Next, the orientation of \( \mathbf{R}_{\text{Arm}}' \) in \( O_{\text{Arm}}\text{-XYZ} \) can be expressed by Equation (15), where the element of the matrix \( \mathbf{R}_{\text{Arm}} \) is presented by \( r_{ij} (i,j=1,2,3) \).

\[
\mathbf{R}_{\text{Arm}}' \mathbf{R}_{\text{Arm}} =
\begin{pmatrix}
\cos \beta & 0 & -\sin \beta \\
\sin \alpha \sin \beta & \cos \alpha & \cos \alpha \cos \beta \\
-\cos \alpha \sin \beta & \cos \alpha \sin \beta & \cos \beta
\end{pmatrix}
\begin{pmatrix}
\cos \sigma & 0 & -\sin \sigma \\
\sin \sigma \sin \gamma & \cos \sigma & \cos \gamma \\
\cos \sigma \cos \gamma & \sin \sigma \cos \gamma & \cos \gamma
\end{pmatrix}
= \begin{pmatrix}
r_{11} & r_{12} & r_{13} \\
r_{21} & r_{22} & r_{23} \\
r_{31} & r_{32} & r_{33}
\end{pmatrix}
\]

(15)

By using Equation (15), the Euler angles \( (\phi, \theta, \psi) \) can be acquired (Yoshikawa, 1988).

\[
\phi = \arctan 2(r_{33}, r_{23}), \quad \theta = \arctan 2\left(\sqrt{r_{11}^2 + r_{21}^2}, r_{33}\right), \quad \psi = \arctan 2(r_{22}, r_{33}) \quad (0 < \theta < \pi)
\]

(16)

Equation (17) can be derived by differentiating Equation (16) with regard to time \( t \) (Yoshikawa, 1988):

\[
\begin{pmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{pmatrix}
= \begin{pmatrix}
\frac{r_{23} r_{31} - r_{21} r_{33}}{(r_{21})^2 + (r_{31})^2} \\
\frac{\sqrt{(r_{13})^2 + (r_{21})^2} - (r_{15})^2 + (r_{31})^2}{(r_{11})^2 + (r_{21})^2 + (r_{31})^2} \\
-\frac{(r_{22} r_{31} + r_{21} r_{32})}{(r_{11})^2 + (r_{31})^2}
\end{pmatrix}
\]

(0 < \theta < \pi)

(17)

\( \dot{\phi}, \dot{\theta}, \dot{\psi} \) are functions of \( \dot{\alpha}, \dot{\beta}, \dot{\gamma}, \dot{\sigma} \). Therefore, by using a matrix \( D \) with element \( d_{ij} (i=1, 2, 3, j=1, 2, 4, 5) \), \( (\phi, \dot{\phi}, \ddot{\phi})^T \) can be expressed as:

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Equation (14) and (18) can be integrated to the following equation.

\[
\left( \begin{array}{c}
\dot{x} \\
\dot{y} \\
\dot{z} \\
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{array} \right) = \left( \begin{array}{c}
C \\
D
\end{array} \right) \left( \begin{array}{c}
\alpha \\
\beta \\
\gamma \\
\sigma \\
h_1' \\
h_2'
\end{array} \right) = \left( \begin{array}{c}
\alpha, \beta, \gamma, \sigma \\
h_1', h_2'
\end{array} \right)
\]  

\tag{19}

Let inverse matrix of \( A \) and \( B \) be \( A^{-1} \) and \( B^{-1} \), which comprise elements \( a_{ij}^{-1}, b_{ij}^{-1} \) (i,j=1,2,3), then \( \alpha, \beta, h_1', \gamma, \sigma, h_2' \) can be derived from Equation (13).

\[
\left( \begin{array}{c}
\alpha \\
\beta \\
h_1'
\end{array} \right) = A^{-1} \left( \begin{array}{c}
l_1' \\
l_2' \\
l_3'
\end{array} \right) = \left( \begin{array}{c}
a_{21}^{-1} a_{22}^{-1} a_{23}^{-1} a_{24}^{-1} l_1' \\
a_{31}^{-1} a_{32}^{-1} a_{33}^{-1} a_{34}^{-1} l_2' \\
\sigma^{-1} l_3'
\end{array} \right)
\]  

\tag{20}

Therefore, by using Equation (19) and (20), the vector representing the posture of end-effector can be acquired.
From the above equation, the Jacobian matrix $J_1$ can be calculated.

### 3.4 Static mechanics

Let force generated and virtual displacement of each actuator be $\mathbf{r}$ and $\Delta l$, and the force generated and virtual displacement of Rod end $P_{RE}$ be $F$ and $\Delta x$. From virtual work principle, the relationship between these two pairs is:

$$ F^T \Delta x = r^T \Delta l $$ (22)

By using Equation (21)

$$ \Delta x = J_1 \Delta l, \quad J_1^T \Delta x = \Delta l, \quad \therefore \Delta l = J_1 \Delta x \quad (J = J_1^{-1}) $$ (23)

Therefore, from Equation (22) and (23), the relation between $F$ and $r$ is acquired.

$$ F^T \Delta x = r^T J_1 \Delta l, \quad F^T = r^T J_1 \quad \therefore F = J_1^T r $$ (24)

### 4. Method of analysis

In this section, an evaluation index based on the Jacobian Matrix is presented, and the process to evaluate possible configurations, i.e., the physical dimension of the shoulder prosthesis is described.

#### 4.1 An estimative index of manipulability: condition number

The condition number (Arai, 1992) was employed as evaluation indicator for the motion characteristics of the Arm mechanism. The condition number is based on the singular value of the Jacobian matrix. The Equation (24) can be described as the expression for how $\mathbf{r}$ is converted into $F$. Furthermore, a singular value decomposition, expressed by Equation (25), can make the property of $J$ even clearer.

$$ J^T = U \Sigma V^T $$ (25)

Here, $U$ and $V$ are 6x6 orthogonal matrixes, which can be described by Equation (26).

$$ U = (u_1, \cdots, u_6)^T, \quad V = (v_1, \cdots, v_6)^T, \quad \Sigma = \text{diag}(\sigma_1, \cdots, \sigma_6), \quad (\sigma_1 \geq \cdots \geq \sigma_6 \geq 0) $$ (26)

Substituting Equation (25) into (24), the relation between $\mathbf{r}$ and $F$ can be rewritten as Equation (27).

$$ F = U \Sigma V^T r $$ (27)

Equation (26) and (27) can be rewritten using the elements of $U$ and $V$.

$$ u_i^T F = \sigma_i v_i^T r $$ (28)

Considering the function of the manipulator, it is preferable that the forces that could be generated at the end of the Rod in all direction are as uniform as possible. That is, it is the
ratio of the maximum singular value to the minimum one, i.e., the condition number, should be close to 1 as much as possible.

Since the condition number of $J^T$ reflects the both the force and torque working at the end of the Rod, in order to conduct proper evaluations, it is necessary to separate the influence of force and torque. Therefore, in the Equation (24), $J^T$ is separated into the part contributing to the force and the one contributing to the torque, and singular value decomposition was conducted at two parts separately. Therefore, $J^T$ is separated as follows.

$$J^T = \begin{bmatrix} J^f_T \\ J^m_T \end{bmatrix}$$

(29)

Here, $J^f_T$ and $J^m_T$ are 3x6 matrixes, so, three singular values $\sigma_{f_i}, \sigma_{m_i}(i=1,2,3)$ exist in each of $J^f_T$ and $J^m_T$. Thus, we use the following three condition numbers as estimative index:

$$C = \frac{\sigma_1}{\sigma_6}$$

(31)

$$C_f = \frac{\sigma_{f_1}}{\sigma_{f_3}}$$

(32)

$$C_m = \frac{\sigma_{m_1}}{\sigma_{m_3}}$$

(33)

### 4.2 An outline of the evaluation process

The following is an outline of the evaluation process.

1. Setting up a coordinate space $\Sigma_{CSI}$;
2. Setting up an initial configuration (physical dimension of the Arm mechanism), and modelling the Arm and human body in $\Sigma_{CSI}$;
3. Defining EF AA (Expected Frequently Accessed Area) and RA (Reachable Area) of the Arm in $\Sigma_{CSI}$;
4. For different length of pneumatic actuators, reflecting translational motion of the actuators, numerically calculating and plotting the Rod end position $P_{RE}'$;
5. Calculating the estimative indexes for all the $P_{RE}'$ in EF AA and RA;
6. Changing the parameters of the Arm mechanism, and going back to recalculating Step 4;
7. After a certain number of loops of execution (Step 4 to 6), evaluating all the configurations to decide configurations optimal for the spatial accessibility (plot number in EF AA) and manipulability.

### 4.3 Modelling the Arm and human body in the coordinate space

A 3D human body model software (HumanWorks) was used for the above-mentioned human body. This HumanWorks model, shown in Fig. 4, 167.0 centimeters tall, is a 50th percentile model of Japanese male based on Japanese Industrial Standards.

Fig. 5(a) shows the coordinate system, $\Sigma_{CSI}$ for the shoulder prosthetic system. It presents not only the geometry of the Arm, and also the EF AA, and their relationship.

As illustrated in the Fig. 5(a), the point of origin is set at the intersection of the median sagittal plane($Y=0$), with the horizontal plane($X=0$) and the coronal plane($Z=0$) passing.
through the acrominon. Positions of the acrominon are assumed as $(0, \pm 170, 0)$. In Fig. 5(c), (d), the size of some parts of human body is presented. Considering the shape and positional relationships of the shoulder, neck, head and the Arm, the Base 1 of the Arm is set at $(-80, 150, 0)$, the axis direction of $O_{B1}$-XYZ (see Fig. 3) is set to conform to the $Z$ axis of the $\Sigma_{C51}$. Moreover, based on the arm size of the 50th percentile model, we estimated the size of the Arm suitable for the human body, and setup initial values for the physical dimension of the Arm (Fig. 5(b)). These initial values, which constitute an initial configuration, are summarized as follows (see Fig. 3 for the meanings of the symbols).

$$h_1 = 100$$
$$h_2 = 170$$
$$l_1 = 250$$
$$r_g = 50$$
$$r_v = 45 \text{ (mm)}$$

Fig. 4. A 3D human body model of HumanWorks.
To Design a Small Pneumatic Actuator Driven Parallel Link Mechanism for Shoulder Prostheses for Daily Living Use

4.4 Important areas in the working space of the Arm

Two important areas in the working space of the Arm are defined for the analysis and evaluation of the Arm. One is the area close to the chest and the median sagittal plane, which is expected to be accessed very frequently during most daily living tasks. This area is the EFAA defined before, and expressed as $\Sigma_{EFAA}$. Another is the area that represents the reachable area $[RA]$ of the end effector, defined as $\Sigma_{RA}$. Geometries of $\Sigma_{EFAA}$ and $\Sigma_{RA}$ are illustrated as in Fig. 6. The volumes of $\Sigma_{EFAA}$ and $\Sigma_{RA}$ are set to 12000cm$^3$ and 75000cm$^3$, respectively.

Fig. 5. The coordinate system $\Sigma_{CS1}$ and the HumanWorks model.

Fig. 6. Geometries of the areas $\Sigma_{EFAA}$ and $\Sigma_{RA}$. 

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4.5 Calculation and analysis
All the calculation was calculated numerically by using Matlab (MathWorks, Inc.). A simplified Arm, as shown in Fig. 7, is drawn for visualization in Matlab. \( P_{RE} \) is calculated by substituting the initial values to Equation (12), with variable length of actuators, which stands for the translational motion of the pneumatic actuators. Three different values were set for each \( l_i' \) (\( i=1, \cdots, 6 \)) in Fig. 3(b). Supposing that the resting length of the actuators are \( LW_i \) (\( i=1, \cdots, 6 \)), and the maximum, minimum, middle increment of the actuators are \( L_{max} \), \( L_{min} \), \( L_{mid} \), then the three different values are \( LW_i + L_{max} \), \( LW_i + L_{min} \), \( LW_i + L_{mid} \) (Fig. 8). Thus, for each Arm configuration, a total number of \( 3^6 = 729 \) sets of calculation were calculated for \( P_{RE} \), then the configuration could be evaluated.

Fig. 7. Models with Matlab.

Fig. 8. Three different values of \( l_i' \).

The estimative index described in section 4.1 was adapted as follows, for evaluating different aspects of the system.
- \( N_{EFAA} \): Number of points plotted in \( \Sigma_{EFAA} \) (Spatial accessibility)
To Design a Small Pneumatic Actuator Driven Parallel Link Mechanism for Shoulder Prostheses for Daily Living Use

- \( N_{RA} \): Number of points plotted in \( \Sigma_{RA} \) (Spatial accessibility)
- \( M_T(C) \): 15 percent trimmed mean condition number \( C \) (Eq. 30) of points plotted in \( \Sigma_{EFAA} \) (Manipulability)
- \( M_T(C_f) \): 15 percent trimmed mean condition number \( C_f \) (Eq. 31) of points plotted in \( \Sigma_{EFAA} \) (Manipulability)
- \( M_T(C_m) \): 15 percent trimmed mean condition number \( C_m \) (Eq. 32) of points plotted in \( \Sigma_{EFAA} \) (Manipulability)

After the calculation and evaluation, the physical dimensions of the Arm structure were changed, and the calculation and evaluation for the new configuration were repeated. Note, in this chapter, only the results of changing \( h_2 \) and \( l_R \) are to be reported. From this process, optimal configurations of the Arm structure could be determined.

5. Results

5.1 Results of the initial configuration

A plot of \( P_{RE} \) for the Arm structure with the initial configuration is shown in Fig. 9, where points in red, blue and gray stand for the \( P_{RE} \) located in \( \Sigma_{EFAA} \), in \( \Sigma_{RA} \) and outside of the both areas, respectively. Basically, the group of points is longitude-axis-symmetric.

![Fig. 9. Plotting \( P_{RE} \) with the initial parameter.](image)

Table 1 shows the values of estimative indexes defined in section 4.5

<table>
<thead>
<tr>
<th>( N_{EFAA} )</th>
<th>( N_{RA} )</th>
<th>( M_T(C) )</th>
<th>( M_T(C_f) )</th>
<th>( M_T(C_m) )</th>
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<td>852240</td>
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<td>1195.5</td>
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</table>

Table 1. Estimative index with the initial parameter.

5.2 Results of other configurations generated by changing parameters

Suppose that the parameters \( h_2 \) and \( l_R \) are changed as in Equation (34), where, beginning with 170mm, 250mm (parameters of the initial configuration) \( h_2 \) and \( l_R \) increase or decrease incrementally by 25mm and 50mm, respectively, and \( i \) is an integer, taking value 0, 1, 2.
\[ h_1 = 170 \pm 25i \]
\[ l_R = 250 \pm 50i \quad (i = 0, 1, 2) \quad \text{(mm)} \]  

\( \text{(34)} \)

Therefore, a total number of 25 combinations could be made, and identified with No.1-1, \( \cdots \), No.1-25, as shown in Table 2. The estimative indexes were calculated for all the combinations. The \( N_{EFAA} \) and \( N_{RA} \) are shown in Fig. 10. The horizontal axis stands for the ID of combination, and vertical axis represents \( N_{EFAA} \) (Fig. 10(a)) or \( N_{RA} \) (Fig. 10(b)).

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Table 2. Combinations of \( h_2 \) and \( l_R \).

Fig. 10(b) shows a tendency that as the \textit{Arm} length \( l_R \) gets longer, \( N_{RA} \) decreases almost monotonically, but there is a steep descent after No.1-21. This can be attributed to the fact that a certain \textit{Arm} length \( l_R \) would make the \textit{Rod} end more likely to go over the \( \Sigma_{RA} \).

Fig. 10. \( N_{EFAA} \) and \( N_{RA} \) of 25 combinations of \( h_2, l_R \).
Whereas, as shown in Fig. 10(a), there are roughly two stages. In the stage after No. 1-13, $N_{\text{EFAA}}$ decreases while vibrating irregularly and strongly. This can be attributed to the reason same as before: a certain Arm length $l_R$ would make the Rod end more likely to go over the $\Sigma_{\text{EFAA}}$. A different point is that the value of No. 1-16, with a smallest $h_2$ ($h_2 = 120 \text{mm}$), shows a large local maximum. It seems $h_2$ affected $N_{\text{EFAA}}$ more than $N_{\text{RA}}$. In the stage before No.1-12, $N_{\text{EFAA}}$ gradually increases as the Arm length gets longer, which means that it is necessary to precisely investigate the possibility of the Arm with shorter length, i.e., smaller $l_R$ and $h_2$. Thus, the Arm with the parameters shown in Equation (35) was investigated.

\[
\begin{align*}
    h_2 &= 100 + 7i \\
    l_R &= 70 + 20i \quad (i = 0, \cdots, 9) \quad (\text{mm})
\end{align*}
\]

A total number of 100 combinations could be made, and identified with No.2-1, \cdots, No.2-100, as shown in Table 3. The estimative index was calculated for all the combinations. The results are shown in Table 3 and Fig. 11, 12.

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Table 3. Combinations of $h_2$ and $l_R$.

As shown in Fig. 11, within the range, as the Arm $l_R$ gets longer, $N_{\text{EFAA}}$ and $N_{\text{RA}}$ changes in the opposite direction: $N_{\text{EFAA}}$ increases and $N_{\text{RA}}$ decreases. Thus, it is reasonable that, prospective solution for the Arm should be specified within this range.
In Fig. 12, the horizontal axis stands for the ID of combination, and vertical axis represents $M_t(C)$ (Fig. 12(a)), $M_t(C_f)$ (Fig. 12(b)) and $M_t(C_m)$ (Fig. 12(c)). There is a steep increase between No. 2-87 and No. 2-88. Since, the smaller value of $M_t(C)$, $M_t(C_f)$ and $M_t(C_m)$ means the better manipulability of the shoulder prosthesis, prospective solutions should be chosen from the combinations before the No. 88.

Apparently, better accessibility requires a bigger value of $N_{EFAA}$ and $N_{RA}$, however, from the aforementioned results, it is clear that within the range investigated (as shown in Fig. 11), they cannot be satisfied simultaneously. That is, $N_{EFAA}$ and $N_{RA}$ should be traded-off depending on which area (EFAA or RA) is more important.

For this purpose, thresholds were determined as follows to reflect different weighting policies and the constraint from manipulability, i.e., $M_t(C_i)$, $M_t(C_f)$, $M_t(C_m)$. The average $\mu_0$ and standard deviation $\sigma_0$ of $N_{EFAA}$, $N_{RA}$, $M_t(C_i)$, $M_t(C_f)$, $M_t(C_m)$ were calculated. For $M_t(C)$, $M_t(C_f)$, $M_t(C_m)$, threshold value was set as $\mu_0+0.5\sigma_0$, which stands for the largest mean value that could be allowed. IN the EFAA-favoured policy, $N_{EFAA}$ should be larger than $\mu_0+0.5\sigma_0$ (upper bound), but $N_{RA}$ should be at least larger than $\mu_0-0.5\sigma_0$ (lower bound). Similarly, in the RA-favoured policy, $N_{RA}$ should be larger than $\mu_0+0.5\sigma_0$, but, $N_{EFAA}$ should be at least larger than $\mu_0-0.5\sigma_0$. Equation (36)-(a) and (b) show the threshold values reflecting the EFAA-favoured and RA-favoured policies, respectively.

![Graph](image-url)
To Design a Small Pneumatic Actuator Driven Parallel Link Mechanism for Shoulder Prostheses for Daily Living Use

Fig. 12. $M_t(C)$, $M_t(C_f)$ and $M_t(C_m)$ of 100 combinations of $h_2$, $l_R$.

By using the Equation (36), 8 configuration candidates were selected. In Table 4, the configurations painted red and blue are selected by Equation (36)-(a) and Equation (36)-(b), respectively.

Furthermore, since $M_t(C)$, $M_t(C_f)$, $M_t(C_m)$ are the mean values for $C$, $C_f$, $C_m$, for the configurations selected by the threshold values shown in the Equation (36), there is a possibility that, at some postures, the manipulability might be extremely bad. Therefore, it is necessary to specify the lower bound for the worst manipulability that could be allowed. The following three additional estimative indexes were defined, which means the configuration with a smaller 3rd quartile (the value of a point that divides a data set into 3/4 and 1/4 of points) would be tolerated. They are only defined for EFAA, because this area requires precise manipulation more than RA.

- $Q_3(C)$: the 3rd quartile of $C$ (Eq. 30) of points in $\Sigma_{EFAA}$
- $Q_3(C_f)$: the 3rd quartile of $C_f$ (Eq. 31) of points in $\Sigma_{EFAA}$
- $Q_3(C_m)$: the 3rd quartile of $C_m$ (Eq. 32) of points in $\Sigma_{EFAA}$
Table 4. Combinations of h2 and l2.

Fig. 13 shows the values of the new estimative indexes Qh2(C), Ql2(C) and Qh2(C) for 100 configurations listed in Table 4. Qh2(C) oscillated with a gradually decreasing peak-to-peak value. Ql2(C), Qh2(C) oscillated with a biggest peak-to-peak value of 2500, and 250 respectively, and turned to stable at a comparatively low level between No.2-50 to No.2-70. Thus it is clear that these new indexes could provide useful information to select optimal Arm configurations further.

The values of all the estimative indexes for the selected configurations (for both EFAA-favoured and RA-favoured policies) are shown in Table 5, and Fig. 14.

Table 5. 8 values of the estimative indexes for selected configurations.

| NO. 2- | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|-------|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|
| h2(mm)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| l2(mm)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| N| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| M(C)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| Qh2(C)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| Ql2(C)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|
| Qh2(C)| 100| 107| 114| 121| 128| 135| 142| 149| 156| 163| 170| 177| 184| 191| 198| 205| 212| 219| 226|

Table 5. 8 values of the estimative indexes for selected configurations.
Fig. 13. $Q_3(C)$, $Q_3(C_f)$, and $Q_3(C_m)$ of 100 configurations listed in Table 4.
It is certain that the selected configuration No.2-29, 30, 34, 35, 36, 41 resulted in a larger $N_{RA}$, and configuration No.2-59, 60 made a larger $N_{EFAA}$. Considering the $N_{RA}$, $N_{EFAA}$ and $Q_3(C)$, $Q_3(C_f)$, $Q_3(C_m)$ together, among the RA-favoured configuration, No.2-29, among the EFAA-favoured, No.2-59 are the optimal configurations.

### 6. Discussion

Optimal configurations were selected, using the estimative indexes proposed. How the selected configurations meet the requirements of the shoulder prostheses for daily living is
the most important concern. Prototyping and experiments in real daily living environment are necessary to give the evaluation. However, on this research stage, preliminary verification could be done by comparing one selected configuration with the initial solution. The comparison was shown in Table 6 and Fig. 15.

Table 6. A comparison between the optimal with the initial configuration.

As shown in Table 6, all the other indexes are improved at a price of 26.47% reduce of $N_{EFAA}$. This could be improved or compensated by 1) including $h_l$, and disk size $r_B$, $r_P$, as design parameters to enable better combinations; 2) employing a flexible backbone; 3) increasing actuators’ operating range by changing pneumatic actuators, or serially connecting the current actuators.

There is another important clue shown in Fig. 15. There are 2 relative features of the selected configuration: 1) plots of the selected configuration are more compact than the initial solution; 2) the center of the plot distribution locates quite far from the center of the EFAA. Due to the two features, there are fewer points plotted in $\Sigma_{EFAA}$. However, if the center of this compact distribution could be directed towards the center of EFAA, much better configuration could be expected. The relocation of the distribution center could be realized by biasing the initial posture of the shoulder prosthesis, i.e., adjusting resting length of actuators.

Considering the fact that the Arm is used as shoulder prosthesis, twisting or bending users’ trunk could also contribute to the posture control. However, this is not preferable, since it could result in fatigue damage accumulation in lower back muscles, due to frequent use of upper limb in daily living. That is why the spatial accessibility would be a very important issue in our future research. Moreover, the existence of singular points should be confirmed, and investigation from the viewpoint of mechanics should be done.
Fig. 15. A comparison between the optimal with the initial configuration.
7. Conclusion

In the research, approach to optimize configuration for shoulder prostheses considering the spatial accessibility and manipulability was proposed. Since for an individual user, the preferable EFAA and RA might be different due to individual difference in daily living style and tasks, and physical constitution, rather than configuration itself, the approach to find the configuration is more important. Thus our research could facilitate the design process of shoulder prostheses with constrained functional elements.

In the near future, estimative indexes to evaluate spatial distribution should be devised, with which the items for further investigation mentioned in the section 6 should be carried out and verified.

8. Acknowledgment

This work was supported in part by a Grant-in-Aid for Scientific Research (B), 2011, 23300206, from the Ministry of Education, Culture, Sports, Science and Technology of Japan, and by the Mitsubishi Foundation.

9. References


Troncossi, M.; Borghi, C.; Chiossi, M.; Davalli, A. & Parenti-Castelli, V. (2009a). Development of a prosthesis shoulder mechanism for upper limb amputees: application of an original design methodology to optimize functionality and


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