Abstract

This article describes the development of a mathematical model of the human hand using a planar multibody formulation with natural coordinates. The multibody model correctly describes the motion and inertial characteristics of the hand as well as its interaction with a hand rehabilitation device under development. The use of non-invasive multibody dynamic tools allows the calculation of the moments-of-force and internal forces at the joints of the hand during the rehabilitation task. A brief description of the anatomy, physiology and of the most common pathologies and injuries of the human hand is also provided for the sake of understanding the mathematical model, the associated rehabilitation device and the main concepts driving its design. The mathematical model is thoroughly described under the scope of the multibody formulation with natural coordinates, in which the position and orientation of the anatomical segments are represented using the Cartesian coordinates of points located in relevant anatomical landmarks of the hand, such as joints and extremities. The kinematic data describing the hand flexion-extension movement was acquired in the movement analysis laboratory and the coordinates of the referred relevant points reconstructed and filtered using a 2nd order Butterworth low-pass filter. Two multibody computational codes were developed in Matlab: one that performs the kinematic analysis of the acquired motion and other that performs its dynamic analysis. The results obtained present biomechanical relevance and can be used in the actual design phase of the rehabilitation device.

Keywords: Hand Biomechanics, Multibody Dynamic Analysis, Biomechanical Model, Articular Moments, Rehabilitation Device.

1. Introduction

The hand is a very important part of the human body. It is used to do a lot of different things as for example to do the precision motion of sewing with a needle or to withstand 20kg when returning home. The function of the hand is unusually important in the human life. The hand is used as a working tool but at the same time its gestures make up the symbols of greeting, request or condemn.

That is why it is so important to quickly restore the largest efficiency of the hand function and movement of persons who, as a result of an accident or disease, have being deprived of these faculties. The fact that there are only a few number of devices on the market to the rehabilitation of the hand creates the need to devise new solutions for a better and more efficient hand rehabilitation. It is in this perspective that the motivation for the work that develops next appears. It is well known that any medical or rehabilitation device must be put to the test before it can be applied to help people with disabilities. With the actual computers and with the right computational methods, it is possible nowadays to construct reliable and accurate computational models that are able to analyze in an integrated way the performance of the device and the effectiveness of its action on the affected biological structure. This is even more important in the early stages of design when no prototype is yet available.

This article describes the development of a mathematical model of the human hand using a multibody system formulation with natural coordinates that correctly describes the motion and behaviour of the human hand and its interaction with the rehabilitation device. From this perspective, the use multibody dynamics tools, has proved to be a successful option to describe systems undergoing large displacements, calculating the moments of force and the internal forces developing in the joints of the human hand during the rehabilitation task. Another important characteristic provided by the use of multibody methodologies, is that the information obtained is the result of the application of mechanical laws of physics to living structures and, therefore, it is not obtained using invasive measuring techniques. The calculation of the reaction forces at the joints and the determination of the moments of force produced by the muscles during the prescribed task are obtained from the solution of a set of equations of motion, assembled in a systematic ways for the biomechanical system under analysis, instead of being obtained using specific force measuring devices.
2. Anatomy and Physiology of the Hand

The hand (manus) is a part of the upper limb and includes the wrist, the metacarpus and fingers. There are 27 bones within the wrist and hand distributed by 3 major areas: the carpal, the metacarpal and the phalangeal. The wrist itself contains eight small bones, called carpals, which are showed in fig. 1: the hamate (1), the pisiform (2), the triquetrum (3), the capitate (4), the lunate (5), the scaphoid (6), the trapezium (7), and the trapezoid (8) (see fig. 1). The carpals connect to the metacarpals. One metacarpal connects to each finger and thumb (Tortora, G., Grabowski, S. R., 2001).

![Fig. 1. Bones of the hand](image)

The hand is composed by 3 types of articular joints: the wrist joint complex with the intercarpal joints, the metacarpophalangeal joints and the interphalangeal joints as depicted in fig. 2a). More information on this subject can be found in (Musiolik, A., 2008). The muscles of the hand are divided into intrinsic and extrinsic muscle groups, see fig. 2b). More information on this subject can be found in (Musiolik, A., 2008).

![Fig. 2. Articular and Muscular structure: a) Joints, b) Partial view of muscles](image)

3. Common Pathologies and Injuries of the Human Hand

The upper limbs have a large number of different genetic and environment derived abnormalities, some of which can be surgically repaired, while others may indicate other syndromes or karyotype anomalies by association. In this work the major types of hand pathologies were reviewed: congenital defects, hand injuries and diseases. More information on this subject can be found in (Musiolik, A., 2008). In all of these pathologies, hand rehabilitation can often be accomplished if proper rehabilitation devices are used.

4. Multibody Systems with Natural Coordinates

In the scope of this article, a multibody system is an assembly two or more planar rigid bodies (also called elements) that can be joined together, in such a way that their relative movement became constrained. The joining of two rigid bodies is called a kinematic pair or simply a joint (Nikravesh, P., 1988), (Haug, E., 1989).
Multibody systems can be also acted up on by external forces. Forces can be conservative like the gravitational acceleration field or non-conservative like the friction force.

In order to describe a multibody system, the first important point to consider is that of choosing a mathematical way of describing its position and motion. In other words, select a set of coordinates that will allow one to unequivocally define the position, velocity, and acceleration of the multibody system at all times. In this work a set of dependent coordinates, called natural of fully Cartesian coordinates was used (Musiolik, A., 2008), (Jalón, J., et. al, 1994).

Dependent coordinates generate a set of algebraic constraint equation that represent the interdependency between these coordinates. Defining the vector of generalized coordinates \( \mathbf{q} \) as the vector that holds all the dependent coordinates, then, the solution of the Kinematic problem resides in obtaining the solution of:

\[
\Phi(\mathbf{q},t) = 0 \quad (4.1)
\]

where \( \Phi \) is the global Kinematic constraint vector , i.e., the vector that contains all the Kinematic Constraint equations of the system, in the homogeneous form. As there are several constraints that are used to define the inputs of the system in time, \( \Phi(\mathbf{q},t) = 0 \) can explicitly depend on \( t \).

It is customary to resort to the well-know Newton-Raphson method, which has quadratic convergence in the neighborhood of the solution and does not usually cause serious difficulties if one starts with a good initial approximation, to solve eq. (4.1). The Newton-Raphson method is based on a linearization of eq. (4.1) and consists in replacing this system of equations with the first two terms of its expansion in a Taylor series around a certain approximation \( \mathbf{q}_i \) of the desired solution:

\[
\Phi(\mathbf{q}_i,t) + \Phi_q(q-\mathbf{q}_i) = 0 \quad (4.2)
\]

where matrix \( \Phi_q \) is the Jacobian matrix of the constraint equations, that is to say, the matrix of partial derivatives of these equations with respect to the dependent coordinates. Eq. (4.2) must be solved iteratively until a solution is found or in other words, when

\[
\mathbf{q}_{i+1} - \mathbf{q}_i = \Delta \mathbf{q} \leq \varepsilon \cong 0 \quad (4.3)
\]

where previous equation represents the iterative procedure of the Newton-Raphson method, and \( \varepsilon \) is a user specified error tolerance.

Calculation of the velocities and accelerations of the system considers that if there cannot exist violation of the associated kinematic constraint equations (4.1), then, the same must also holds true for the velocities and accelerations associated to these constraints, i.e:

\[
\Phi(\mathbf{q},\mathbf{q},t) = 0 \quad (4.4)
\]

for the velocities , and

\[
\ddot{\Phi}(\mathbf{q},\mathbf{q},\dot{\mathbf{q}},t) = 0 \quad (4.5)
\]

for the accelerations. Expanding eq. (4.4) and (4.5) the following equations are obtained:

\[
\Phi_q(q)\dot{q} = -\Phi_t = \mathbf{v} \quad (4.6)
\]

\[
\Phi_q(q)\ddot{q} = -\Phi_t - \Phi_q\dot{q} = \gamma \quad (4.7)
\]

Vector \( \mathbf{v} = -\Phi_t = -\frac{\partial \Phi}{\partial t} \) is referred to as the rigid-hand-side of the velocity constraint equations.

Vector \( \gamma = \ddot{\mathbf{v}} - \Phi_q\dot{q} \) is referred to as the vector of the rigid-hand-side of the acceleration constraint equation where \( \dot{\mathbf{q}} \) is the vector of generalized dependent velocities, and \( \ddot{\mathbf{q}} \) is the vector of generalized dependent accelerations.

Dynamic analyses are much more complicated to solve than kinematic ones. The major characteristic about dynamic problems is that they involve the forces that act on the multibody system and its inertial characteristics namely its mass, inertia tensor and the position of its centre of gravity.
According to Newton-Euler equations, the equations of motion of an unconstrained multibody system can be written as:

\[ M\ddot{q} = g \]  \hspace{1cm} (4.8)

where \( g \) is generalized external force vector and \( M \) is the mass matrix containing the mass and inertial characteristics of each rigid body.

If a set of constraint bodies is considered instead, then the equation of motion will become:

\[ M\ddot{q} + g^{(0)} = g \]  \hspace{1cm} (4.9)

where an additional term \( g^{(0)} \) is added representing the generalized internal force vector arising from the kinematic constraints imposed to the system. Using the Lagrange multiplier’s method, these forces can be expressed as a function of the Jacobian matrix (that provides the direction of these forces) and a vector \( \lambda \) of unknown Lagrange multipliers (that describes their magnitude) as:

\[ g^{(0)} = \Phi_q^T\lambda \]  \hspace{1cm} (4.10)

Substituting eq. (4.10) in eq. (4.9), the resulting equation of motion becomes

\[ M\ddot{q} + \Phi_q^T\lambda = g \]  \hspace{1cm} (4.11)

Because \( \lambda \) and \( \ddot{q} \) are unknowns, it is necessary to add equation (4.12) to eq. (4.11) to solve this problem:

\[ \Phi_q\ddot{q} = \gamma \]  \hspace{1cm} (4.12)

resulting the final expression of the system of the equations of motion of the model:

\[
\begin{cases}
M\ddot{q} + \Phi_q^T\lambda = g \\
\Phi_q\ddot{q} = \gamma
\end{cases}
\]  \hspace{1cm} (4.13)

The mass matrices will undoubtedly depend on the type of coordinates chosen for the representation of multibody system. In this work, the use of Natural Coordinates lead to an elaborated deduction of this matrix that remains outside the scope of this article. The interested reader is referred to the work of (Jalón, J. and Bayo, E., 1994).

5. Multibody Model of the Hand and Rehabilitation Device

A lot of pathologies can affect the human hand: congenital defects, several types of hand injuries (including fractures), tendon and ligament injuries and hand diseases. These pathologies interfere directly with the hand function and movement as they produce damage in the neurological and musculo-skeletal structure of the hand. Hand rehabilitation can be accomplished using proper rehabilitation devices. These devices are able to improve hand function and movement, restoring (in many cases) its normal activity.

Here, a computational model of a new rehabilitation device is constructed using the multibody formulation. This type of computational models are important in all phases of the design of a new product, but its application is particularly relevant in the early design phase when no prototype is yet available.

Although a search for hand rehabilitation devices reveals that there are already available in the market several different types of models, with different function and purposes, it is also true that there is still a lot to develop in this field, see thesis (Musiolik, A., 2008).

The rehabilitation device that is now proposed is specially aimed to help patients with partial paresis of the fingers acquired after a Cerebral Vascular Accident (CVA), although more general applications can be considered. The device under development is presented in figure 3a). There one can see the physical prototype made of wood and rope and its virtual counterpart made in the geometrical modeler Unigraphix 5.0, see fig. 3b).
The device is conceived for active practices of the hand allowing the resistance relief of the rectifier muscles of the fingers. The resistive force is generated by a set of weights that are hanged in strings that attach to each finger. This weight may vary from person to person and from pathology to pathology. The attachment of the strings to the fingers is made using a simple velcro stripe. The device allows both hands to work although it can be used independently for each hand. Hands are firmly immobilized using proper hand immobilizer. The position of the vertical support can be tuned to meet patient’s anthropometrics.

Considering the biomechanical system to analyse, represented in fig. 3a) and composed by the hand, lower arm and rehabilitation device, the decision (in terms of constructing a planar multibody model with natural coordinates capable of describing the physical one), is to consider that the lower arm is irrelevant for the analysis and that it can be removed if the kinematics of the wrist were properly considered. Therefore the model includes the hand, starting at the metacarpus and finishing in the distal phalange of the index finger, as depicted on fig. 4. The interaction with the rehabilitation device is only considered in dynamic terms and is considered by introducing a constant force with magnitude equal to the gravitational force produced by the weight and variable direction prescribed by the unit vector going from the attachment point of the hand to the attachment point in the device.

As it can be observed from figure 4, the multibody model is described by four rigid bodies (the metacarpal, the proximal phalange, the middle phalange, the distal phalange) interconnected by 3 revolute joints. Considering that each rigid body requires 2 points to be properly described and that revolute joints are explicitly described by 2 independent points, then the model requires a total number of 8 points, (i. e., 16 natural coordinates) that are put together in vector:

\[ \mathbf{q} = [x_1, y_1, x_2, y_2, x_3, y_3, x_4, y_4, x_5, y_5, x_6, y_6, x_7, y_7, x_8, y_8]^T \]  \hspace{1cm} (5.1)

A closer analysis of the proposed model reveals that it possesses 6 degrees-of-freedom, respectively the 2 translations and 1 rotation of the wrist joint and the 3 rotations of the revolute joints. Therefore, the number of required kinematic constraints, required to express the dependencies among the Natural Coordinates is equal to the difference between the number of coordinates and the number of the system’s degrees of freedom, i. e., 16-6=10 kinematic constraints.

These kinematics constraints are presented hereafter and expressed by algebraic equations with different natures: 4 kinematics constraint equations of rigid body type that are used to preserve the
constant length of rigid bodies I to IV; 6 kinematic constraint equations of revolute joint type that are used to describe the 3 revolute joints; and 6 kinematic constraint equations of kinematic drivers type that are used to fully prescribe the motion of the system during the kinematics and dynamics analyses preformed.

In analytical terms, these equations are represented as:
- Rigid body type (constant length):
  
  Body I:
  \[ \Phi_1 = \mathbf{r}_{12}^T \cdot \mathbf{r}_{12} - L_{12}^2 = (x_2 - x_1)^2 + (y_2 - y_1)^2 = \]

  \[ (5.2) \]

  Body II:
  \[ \Phi_2 = \mathbf{r}_{34}^T \cdot \mathbf{r}_{34} - L_{34}^2 = (x_4 - x_3)^2 + (y_4 - y_3)^2 = \]

  \[ (5.3) \]

  Body III:
  \[ \Phi_3 = \mathbf{r}_{56}^T \cdot \mathbf{r}_{56} - L_{56}^2 = (x_6 - x_5)^2 + (y_6 - y_5)^2 = \]

  \[ (5.4) \]

  Body IV:
  \[ \Phi_4 = \mathbf{r}_{78}^T \cdot \mathbf{r}_{78} - L_{78}^2 = (x_8 - x_7)^2 + (y_8 - y_7)^2 = \]

  \[ (5.5) \]

  Where the inner product of vector was used to prescribe these relations between the coordinates.
- Revolute joint type:
  
  Joint R1:
  \[ \Phi_{5,6} = \mathbf{r}_3 - \mathbf{r}_2 = \begin{bmatrix} x_3 - x_2 \\ y_3 - y_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]

  \[ (5.6) \]

  Joint R2:
  \[ \Phi_{7,8} = \mathbf{r}_5 - \mathbf{r}_4 = \begin{bmatrix} x_5 - x_4 \\ y_5 - y_4 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]

  \[ (5.7) \]

  Joint R3:
  \[ \Phi_{9,10} = \mathbf{r}_6 - \mathbf{r}_6 = \begin{bmatrix} x_7 - x_6 \\ y_7 - y_6 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]

  \[ (5.8) \]
- Kinematic drivers type:

  Drivers D1 and D2 (translation of point 8):
  \[ \Phi_{11,12} = \begin{bmatrix} x_8 - x_8^*(t) \\ y_8 - y_8^*(t) \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \]

  \[ (5.9) \]

  Driver D3 (angle of the wrist, called \( \theta_4 \), see fig. 5):
  \[ \Phi_{13} = \mathbf{r}_{78} \times X - L_{78} \sin \theta_4(t) = -(y_7 - y_8) - L_{78} \sin \theta_4(t) = 0 \]

  \[ (5.10) \]

  Driver D4 (angle between the metacarpal and the proximal phalange, called \( \theta_3 \), see fig. 5):
  \[ \Phi_{14} = \mathbf{r}_{78} \times \mathbf{r}_{65} - L_{78} \cdot L_{65} \cdot \sin \theta_3 = \]

  \[ -(y_8 - y_7) \cdot (x_5 - x_6) + (x_8 - x_7) \cdot (y_5 - y_6) - L_{78} \cdot L_{56} \cdot \sin \theta_3(t) = 0 \]

  \[ (5.11) \]

  Fig. 5. The hand with the angles \( \theta_3 \) and \( \theta_4 \)

  Driver D5 (angle between proximal phalange and middle phalange, called \( \theta_2 \), see fig. 6):
  \[ \Phi_{15} = \mathbf{r}_{56} \times \mathbf{r}_{43} - L_{56} \cdot L_{43} \cdot \sin \theta_2(t) = \]

  \[ -(y_6 - y_5) \cdot (x_3 - x_4) + (x_6 - x_4) \cdot (y_3 - y_4) - L_{56} \cdot L_{43} \cdot \sin \theta_2(t) = 0 \]

  \[ (5.12) \]
Driver D6 (angle between the middle phalange and the distal phalange, called $\theta_1$, see fig. 6):

\[
\Phi_{16} = \mathbf{r}_{34} \times \mathbf{r}_{21} - L_{34} \cdot L_{21} \cdot \sin \theta_1(t) = \\
= -(y_4 - y_3) \cdot (x_1 - x_2) + (x_4 - x_3) \cdot (y_1 - y_2) - L_{34} \cdot L_{12} \cdot \sin \theta_1 = 0 \quad (5.13)
\]

The kinematic constraints presented before are grouped together in vector $\Phi$, see thesis (Musiolik, A., 2008).

The Jacobian matrix plays one of the most important roles in kinematic and dynamic analyse of a multibody system. By definition the Jacobian matrix is the partial derivative of the vector of global kinematic constraints in order to the generalise coordinates vector. Results of the associated Jacobian matrix to this model are presented in (Musiolik, A., 2008).

General expressions for vector $\nu$ and $\gamma$ were provided before. These vectors present the right-hand side of the velocity and acceleration constraint equations respectively. Results of the associated vectors to this model are presented in (Musiolik, A., 2008).

In order to analyze the movement of the hand a set of 4 flexion – extension hand movements were collected using the BTS (Body Training Systems) system with six cameras in the Laboratory of Biomechanics of the Silesian University of Technology in Poland.

The movement acquisition consisted in recording the coordinates of a set of 7 markers (see fig. 7a) (6 in the lower arm and hand and 1 in the rehabilitation device) as depicted in fig. 7b). The subject was a healthy young female with 23 years old and with no hand pathologies. The measured lengths of the subject's hand were very similar with the ones found when averaging the reconstructed values obtained from the BTS system and therefore these average lengths were use instead of the measured ones with the purpose of comparing the kinematics obtained with the driven multibody model with the kinematics obtained directly from the movement laboratory. In table 1 the average lengths are provided, together with the mass and inertial characteristics which are introduced next.

The dynamic analysis of the hand requires the prescription of the hand masses and inertias to the dynamic multibody program.
A search in the available literature also confirm the scarcity of such data, although the values for the masses could be obtained from (Biryukova, V. and Yourovskaya, 1994). These values are presented in Table 1 together with the values of the length, radius and polar inertias of the 4 rigid bodies of the model. It was consider that the total mass of the hand was 1 kg.

<table>
<thead>
<tr>
<th>Body</th>
<th>Mass [kg]</th>
<th>Length [m]</th>
<th>Radius [m]</th>
<th>Inertias [kg m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.007</td>
<td>0.02101</td>
<td>0.0075</td>
<td>$1.128\times10^{-6}$</td>
</tr>
<tr>
<td>II</td>
<td>0.014</td>
<td>0.01910</td>
<td>0.0075</td>
<td>$1.899\times10^{-6}$</td>
</tr>
<tr>
<td>III</td>
<td>0.030</td>
<td>0.03008</td>
<td>0.010</td>
<td>$9.798\times10^{-6}$</td>
</tr>
<tr>
<td>IV</td>
<td>0.662</td>
<td>0.07717</td>
<td>0.015</td>
<td>$1.351\times10^{-3}$</td>
</tr>
</tbody>
</table>

The masses presented in Table 1 include the masses of the corresponding bones plus the masses of all adjoining muscles (Biryukova, V. and Yourovskaya, 1994). The polar inertias were calculated using the approximation to a solid cylinder given the expression $I = ml^2/3 + mr^2/4$. The center of mass of each rigid body was considered to be located in the middle of each rigid segment.

Kinetic data refers to the values of external forces and moments applied upon the system. In this case, since the movement occurs in a plane perpendicular to the direction of the earth gravitational field, the gravitational force is not applied. Therefore according to fig. 8b) the only external force acting on the system is the one applied by the string and corresponding weight. The magnitude of this force is always constant and equal to $F = m_w g$ and its direction is coincident with the direction followed by the string.

6. Results and Discussion

The model described before was implemented in two Matlab programs: one only for kinematic analysis and other for dynamics analysis. The source codes of these programs can be found in (Musiolik, A., 2008).

From the results presented in fig. 8, it is clear that from the kinematics point of view, the conditions imposed by the constraint equations are being respected as the values of the norms of $\Phi$, $\Phi$ and $\Phi$ are always smaller than $1.5\times10^{-7}$, $8.0\times10^{-6}$ and $1.0\times10^{-4}$ respectively. Values in abscissa represent frame numbers.

The results clearly show the four flexion-extension cycles of the hand. It also can be seen that drivers far away from the wrist joint present a more noisy behavior, indicating that lower-cut-off frequencies could have been used.
The results in terms of drivers, velocities and accelerations also show that these quantities are consistent with drivers positions and velocities respectively, see fig. 9.

The kinematic analysis of the drivers also show that maximum flexion-extension angular velocities oscillate between 0.5 rad/s for the wrist joint to 4 rad/s for the metacarpal-phalangeal joint. Values of 1 rad/s to 2 rad/s can be found for the maximum angular velocities of the top and middle interphalangeal joints, respectively.

Fig. 9. Kinematic drivers for the analysis: angles, angular velocity and angular acceleration of each joint

From the analysis of the results it can be seen that in terms of positions, these are consistent with the kinematic data obtained from the laboratory indicating that the drivers are working properly. Moreover, it can also be observed that the velocities are compatible with positions, and accelerations with velocities.

The values for the velocities and accelerations are within the expected physiological range for a normal hand. In absolute values velocities never exceed 0.2 m/s for any of the points independently of the hand being flexing or extending.

Accelerations are still a bit noisy especially for points further away from the wrist, indicating that probably smaller cut-off frequencies could have been used. However, in absolute values, accelerations never surpass 2.0 m/s$^2$ and in many cases they are bellow 0.5 m/s$^2$. These results are within the expected range accelerations for a hand with no pathologies. On fig. 10 kinematic of point 1 and 2 are presented.

Fig. 10. Kinematics for point 1 and 2

In the revolute joints R2 and R3 (and also at the wrist attachment point) one can see that the reaction forces are following the direction and the magnitude of the external applied force. This results
was expected since there are no gravitational component present and inertia forces are small since accelerations are also small, and proves that the model is working probably in terms of the calculation of the joint reaction forces. Reactions in revolute joint R1 are practically null. The first obvious observation is that the moments at the joint R1 is almost zero, since no forces are applied to body I. Moreover, moments have similar behavior in all joints but with a tendency to grow as one approximates the wrist joint, see fig. 11.

7. Conclusions and Future Developments

In this work a computational model for the kinematic and dynamic analysis of 2D hand motions was presented using a multibody formulation with natural coordinates. In the framework of the proposed methodology, two problems have been analyzed: kinematic problems to study the movement of the hand, and dynamic problems to study internal forces and articular moments. The model developed in this work was able to analyse the actual design of the rehabilitation device and can be easily adapted to analyse other design alternatives.

The model proposed is robust but simple. This means that there are other important features that can be implement in the future such as muscle contraction dynamics and Electromyography (EMG) comparative analysis.

8. References


