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Task analysis and kinematic design of a novel robotic chair for the management of top-shelf vertigo

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1. Introduction

The present work addresses the task analysis and the kinematic design of a novel robotic chair to be used for diagnosing and treating Benign Paroxysmal Positional Vertigo (BPPV).

The task analysis process is based on: 1) Direct specifications given by well-trained doctors; 2) Theoretical considerations built upon a mathematical model describing BPPV dynamics.

BPPV is the most frequent cause of vertigo and it is characterized by intense symptoms of dizziness and nausea of short duration which are induced by a postural variation of the patient. A common name for BPPV is "top-shelf vertigo", since dizziness often occurs when tilting back the head, such as when looking at objects on the top shelf. In the elder patients, it represents a frequent cause of equilibrium loss and consequent possible traumatic injuries. Sometimes BPPV symptoms disappear spontaneously but more often they tend to last for months or even years if not adequately treated. It was estimated that 20% of the patients that complain about dizziness are affected by BPPV (approximately 64 in 100,000 people per year in Northern America (Baloh et al., 1989; Froehling et al., 1991; Honrubia et al., 1996)).

BPPV is a malfunction of the vestibular system which is the sensory structure that mainly contributes to the equilibrium. The vestibular system is situated inside the cranium and comprises three fluid-filled semicircular canals (SCC) namely Horizontal Canal (HC), Posterior Canal (PC) and Anterior Canal (AC) (Figure 1(a)) whose duty is the perception of the body's angular motion.

Even though data relating SCC's mutual orientation are sparse, multiple studies of inter-SCC angles concluded that canals are close to perpendicular. Anyway, the relative orientation of the SCC is characterized by a certain degree of disparity within the population of individuals and it can be described by a mean value and its standard deviation (Della Santina et al., 2005; Shinichiro et al., 2005). In media, AC lies on a plane inclined approximately 45° with respect to the body's sagittal plane, PC lies on a plane inclined 45° but in the opposite direction, HC is perpendicular to the other two canals and it is inclined approximately $15\text{--}20^\circ$ with respect to the body's horizontal plane (Figure 1(b)).

The body rotation is sensed through a sensory membrane (*cupola*) which is deflected by the action of the fluid contained in the SCC. Two identical sensory structures are symmetrically disposed with respect to the body's sagittal plane (six SCC in total).

Fig. 1. Human vestibular system and BPPV.

The physiological cause of BPPV is the abnormal presence of calcite particles, named *otoconia* or *otoliths*, within the SCC. It is believed that the presence of otoconia within the SCC could interfere with their normal functioning and could induce a false sensation of motion when in reality the head is kept still.

Concerning the genesis of BPPV, the otoconia separate from their original location within the inner ear and are brought into the canals by normal head movements in everyday life. The medical community have proposed two mechanism to explain BPPV: *cupulolithiasis*, in which otoconia attach directly to the cupula, and *canalithiasis*, in which otoconia settle through the canals and exert a fluid pressure across the cupula (Figure 1(c)). A third and minor theory states that BPPV is caused by calcite dust which is gradually absorbed by the soft tissues causing BPPV symptoms to disappear spontaneously.

Different techniques can be used for BPPV diagnosis and treatment. Most techniques consist in a series of movements of the cranium of the patient in different spatial positions and orientations (repositioning maneuvers or RM, (Brandt & Daroff, 1980; Epley, 1992; Pagnini et al.,

1989; Semont et al., 1980)). RM are executed manually by the doctor and are designed so as to drive otoconia all the way around and out of the canal, so that they settle in the *vestibule/utricle* (Figure 1(a)). As the otoconia reach this position BPPV symptoms disappear.

The success of the RM in most clinical cases has raised an emerging consensus that canalithiasis is the more likely mechanism for BPPV. On the other hand, recent publications (House & Honrubia, 2003) suggest that both canalithiasis and cupulolithiasis are possible.

Concerning BPPV diagnosis, the side (left or right) and the SCC affected by BPPV can be predicted through the observation of the direction of an anomalous eye movement (nystagmus). The nystagmus is evoked by the vestibular-ocular reflex (Raphan et al., 1979; Robinson, 1977) as a result of abnormal stimulation caused by the presence of otoconia within the interested canal. It is believed (Squires et al., 2004) that the size (and mass) of the otoconia dispersed within the SCC is proportional to the intensity of the nystagmus.

Alike the treatment methodology, the diagnosis is carried out through a series of maneuvers called diagnostic maneuvers (DM) during which the doctor recognizes the existence and typology of nystagmus and decides which RM has to be used as treatment. DM are carried out a second time after the treatment: the absence of nystagmus during a subsequent DM represents the marker of the healing.

It has been shown (Epley, 1992) that DM/RM are efficient in 80% of the cases when executed by a well trained doctor. Possible failures can be caused by: (1) a not correct diagnosis; (2) the presence of otoconia in more than one SCC at the same time; (3) a sensible variation of the SCC orientation with respect to the theoretic orientation upon which RM are designed; (4) otoconia which stick to the SCC walls during RM and therefore do not reach the desired final position. If RM are not successful, surgery becomes necessary.

In any case, manual maneuvers present a series of limits such as: (1) very poor repeatability of the trajectories and subsequent impossibility of standardization, (2) limited capability of moving and orienting the patient, especially in case of obese people or elderly with mobility hindrances (where abrupt body/neck's movements should be avoided).

In practice, the efficiency of the present therapeutical methods could be highly improved if:

- A sensorial system capable of recognizing/measuring the existence and typology of nystagmus is employed. Such sensors are commercially available (Figure 2(a)) but it is impossible to correlate their data with the instantaneous pose of the patient during manual RM. Therefore, those devices should be either integrated with a system capable of precisely manipulating the human body or provided with a position/orientation sensor.
- RM and DM are adapted to the need and specific SCC orientation of the single patient. A 3D model of the vestibular system (including SCC morphology, position and orientation within the head) can be made available via TAC or MRN (Figure 2(b)) and specific software (Arnold et al. (1997), Figure 2(c)).
- A purposely designed robotic system is available with the capability of generating fully controllable trajectories with adequate kinematic and dynamic characteristics and adequate repeatability (Nakayama & Epley, 2005).

Besides the improved efficiency of the maneuver, a manipulator purposely designed for the study of BPPV could give a better insight of the physiological mechanisms that cause this disease. Past research has been focused on quantitative modeling of healthy vestibular activity only whereas the discussions around BPPV are nowadays still qualitative. A quantitative analysis is therefore necessary to fully understand the dynamics of top-shelf vertigo and to

Fig. 2. Different tools used in the study of the vestibular activity.

find unambiguous treatment methodology.

On the basis of the aforementioned considerations, this chapter focuses on: 1) The development of a mathematical model which describes the dynamics of BPPV to be used for a reasonable planning of efficient RM; 2) The topological and dimensional synthesis of a serial robot for manipulating the human body and capable of overcoming those limitations which arise during manual RM. The outcome of this work will be useful for selecting the manipulator's actuation system and for optimizing its mechanical structure. On the other hand, some considerations outlined in the following sections are generally interesting when existing RM are critically compared in terms of efficacy.

Note that, if not explicitly reported, all the angles are indicated in radians, the lengths are in meters and the functions' time dependence is omitted for brevity.

2. General aspect of BPPV treatment methodologies

Figures 3(a), 3(b), 3(c) report, as instances, the schematics of a well known DM, namely the Dix-Hallpike DM (Dix & Hallpike, 1952), and of two RM, namely the Epley and the Semont maneuver (Epley, 1992; Semont et al., 1980). A survey of known DM and RM can be found in (Parnes et al., 2003).

In the Dix-Hallpike DM, the patient is brought from supine to seated position keeping the head turned 45° on one side and extended about 20° backward. If the test is positive the maneuver will cause the eyes to jump upward and twist.

The Epley RM, for treating BPPV of PC, involves sequential movements of the head into four different positions, keeping each position for roughly 30 seconds.

The Semont RM, for treating BPPV of PC, is a procedure where the patient is quickly moved from lying on one side to lying on the other. Despite being 90% effective after 4 treatment sessions, it is a vigorous maneuver that can be dangerous when treating elderly people and it is not currently favoured in the US. Moreover, the same inertial forces applied during this RM cannot be easily applied when treating BPPV of HC (where another RM is used i.e., the Pagnini RM (Pagnini et al., 1989)).

From a kinematic point of view, the existing maneuvers are classifiable in:

- RM that rely on the interaction between otoliths and gravity and therefore are based upon otoconia's sedimentation within the SCC. A typical example is the Epley RM. From a kinematic point of view, these maneuvers are based on the orientation of the

human body with respect to gravity and can therefore be realized with an RR structure (neglecting possible joints' limits).

- RM that rely both on otoconia sedimentation and on inertial forces due to rapid postural variation of the patient. It is believed that the inertial forces are capable of breaking the particle-walls interactions that could prevent the otoconia from moving under the effect of gravity. Typical examples are the Semount and the Pagnini RM. From a kinematic point of view, these maneuvers are based on both orienting and positioning the human body with specified trajectories.

As it has been underlined in the previous section, it is possible to enhance RM' efficacy by adding a certain degree of flexibility in the execution of different poses which would allow for the investigation of manually unfeasible maneuvers.

Several cases of robots employed for human handling can be found in the fields of virtual simulation or entertainment; for instance, the RoboCoaster from Kuka Roboticker GmbH (Kuka, 2004), is a six axis serial robot capable of carrying two passengers in programmable ride sequences. A more specific example is the Omniax Positioning System (OPS) designed and manufactured at the Portland Otologic Clinic by Eng. William Scott following Dr. J. M. Epley specifications (Nakayama & Epley, 2005) precisely for BPPV's diagnosis and treatment. The system is basically a moving chair that controls the patient's orientation by providing 360° rotations along two fixed axis plus a third axis for adjusting the pitch plane. By using the OPS, Nakayama and Epley have already demonstrated that a 360° maneuverability and repeatability can improve capabilities for managing BPPV. However, in their work, nothing is said about the application of controlled major inertial forces neither about the possibility of specifying the otoconia trajectory with respect to the SCC position. In practice, being an orienting device, the OPS cannot overcome the limitations of every RM relying on otoconia sedimentation.

In particular, the otoconia is an irregularly shaped rigid particle which might stick to the SCC soft walls. Therefore: 1) Controlled inertial forces could be useful to break the particle-wall interaction (as reported in Squires et al. (2004)); 2) A treatment strategy which prevents the otoconia from touching the SCC as the maneuver has started could increase the rate of success of non-invasive therapies.

The next section further addresses this issue.

3. Dynamic Model for BPPV

This section describes an idealized dynamic model of a single otoconium (hereafter also referred to as "the particle") moving inside a SCC. The aim of the model is to numerically simulate the particle's motion in the case of canalithiasis (Figure 1(c)). An analytical description of the mechanics of cupulolithiasis can be found in (Rajguru et al., 2004).

Similarly to the model proposed by Obrist & Hegemann (2008), a series of simplifying assumptions are made:

- The analysis of the otoconium motion is limited to regions where the SCC can be modeled as a circular toroid. This is in contrast with (Squires et al., 2004) where a SCC with varying cross sectional area is considered;
- The otoconium is considered as a sphere whose radius is negligible with respect to the SCC cross section;
- The radius of the SCC cross section is negligible with respect to the curvature of the circular toroid (Squires et al., 2004). This assumption allows to consider the SCC as a straight circular cylinder when calculating the Stokes drag force acting on the particle.

It is worth saying that an accurate prediction of the otoconium motion is not achievable for the many simplifications that have been made and for the uncertainties of the parameters describing the SCC and otoconium dynamics. However, a rough estimation of the particle trajectory is useful for verifying the effects of the maneuvers performed during BPPV therapy. A suitable compendium of the effects acting on the otoconium inside the SCC can be found in Obrist & Hegemann (2008) and Squires et al. (2004).

(a) Dix-Hallpike diagnostic maneuver.

(b) Epley repositioning maneuver.

(c) Semont repositioning maneuver.

Fig. 3. BPPV diagnostic and treatment maneuvers. Courtesy of St. Orsola Hospital, Bologna (Sec. 7).

Fig. 4. Omniax positioning system (Nakayama & Epley, 2005).

Fig. 5. Forces acting on the otoconium during an SCC planar motion.

Referring to Figure 5, the otoconium is subjected to the gravity field (the force f_g), to the inertial forces arising during its motion (the force f_I), and to the hydrodynamic effects due the presence of the SCC fluid that generates a Stokes drag (the force f_v caused by the relative motion of otoconium within the SCC).

In Squires et al. (2004): 1) Data that correlate the otoconium mass with the intensity of the nystagmus are provided; 2) An expression for the SCC fluid viscosity coefficient with respect to the otoconium's distance from the SCC walls is theorized. A cutoff particle-wall lubrication gap is also considered resembling the effects of the SCC fluid viscosity during the movement of the otoconium along the SCC walls. Similarly, in this chapter, such distance-dependent behavior has been included leading to an over-damped response of the otoconium during a possible impact with the SCC walls.

The model considered hereafter, differently from (Obrist & Hegemann, 2008), takes into account the motion of SCC and otoconium on a plane perpendicular to the SCC axis (conceived as a circular toroid). Thus, the center of the SCC, (point O_{SCC} in Figure 5) can move on the

Description	Symbol	Value	Unit
SCC mass (due to control)	m_c	1	kg
SCC inertia moment (//)	I_{c_z}	1	$\text{kg} \cdot \text{m}^2$
SCC mean radius	r_{mean}	$3.2 \cdot 10^{-3}$	m
SCC inner wall radius	r_{min}	$3.12 \cdot 10^{-3}$	m
SCC outer wall radius	r_{max}	$3.28 \cdot 10^{-3}$	m
SCC wall stiffness	k_c	10^{-3}	$\text{N} \cdot \text{m}^{-1}$
SCC wall damping	b_c	10^{-6}	$\text{N} \cdot \text{s} \cdot \text{m}^{-1}$
Particle mass	m_o	$3.88 \cdot 10^{-12}$	kg
Particle density	ρ_o	$2.7 \cdot 10^3$	$\text{kg} \cdot \text{m}^{-3}$
Particle radius	r_o	$7 \cdot 10^{-6}$	m
Fluid (endolymph) viscosity	η	10^{-6}	$\text{m}^2 \cdot \text{s}^{-1}$
Fluid (endolymph) density	ρ	10^3	$\text{kg} \cdot \text{m}^{-3}$
SCC-particle gap	r_{gap}	$1 \cdot 10^{-6}$	m
Gravity acceleration	g	9.81	$\text{m} \cdot \text{s}^{-2}$

Table 1. Parameters of the SCC-otoconium dynamic model.

Cartesian plane along the $\mathbf{x_B}$ and $\mathbf{y_B}$ directions (Figure 5, where $(\mathbf{xyz})_B$ is an absolute frame attached to the ground), and the SCC is free to rotate with respect to an axis that passes through its center and is perpendicular to the motion plane.

Referring to Figure 5, the angular position and angular velocity of the SCC are indicated by γ and $\dot{\gamma}$ respectively. The otoconium is considered as a sphere of constant radius with concentrated mass at its center and free to move inside the SCC.

It is convenient, from the point of view of modeling the system motion, to express the otoconium position with respect to the SCC center in polar coordinates. The position of the otoconium with respect to the SCC center is then indicated by the angular position β (measured with respect to a frame attached to $\mathbf{O_{SCC}}$ and axis parallel to $\mathbf{x_B}$ and $\mathbf{y_B}$) and the distance r from the center ($\dot{\beta}$ and $\dot{r}$ indicating the time derivatives of such variables). The physical parameters considered in the dynamic model and the nomenclature used in the following are reported in Tab. 1.

Let us define:

- $\mathbf{q_c} = [x \ y \ \gamma]^T$ as the vector of coordinates of the SCC center $\mathbf{O_{SCC}}$ with respect to $(\mathbf{xyz})_B$ ($\dot{\mathbf{q_c}}, \ddot{\mathbf{q_c}}$ being first and second time derivative of $\mathbf{q_c}$);
- $\mathbf{q_o} = [\beta \ r]^T$ as the vector of the otoconium coordinates ($\dot{\mathbf{q_o}}, \ddot{\mathbf{q_o}}$ being first and second time derivative of $\mathbf{q_o}$);
- $\boldsymbol{\tau_c}$ as the vector of the forces applied to the SCC (or, more generally, to the patient body);
- $C_{\gamma\beta} = \cos(\gamma + \beta)$;
- $S_{\gamma\beta} = \sin(\gamma + \beta)$.

By taking into account the forces $\mathbf{f_g}$, $\mathbf{f_I}$ and $\mathbf{f_V}$ and using the Euler-Lagrange formalism, the dynamics of the system can be described as follows:

$$\mathbf{M_c} \ddot{\mathbf{q_c}} = \boldsymbol{\tau_c}$$

(1)

$$\begin{aligned} &\mathbf{M_o}(\mathbf{q_o}) \ddot{\mathbf{q_o}} + \mathbf{M_{co}}(\mathbf{q_c}, \mathbf{q_o}) \ddot{\mathbf{q_c}} + \mathbf{C_o}(\mathbf{q_o}, \dot{\mathbf{q_o}}) \dot{\mathbf{q_o}} \\ &\quad + \mathbf{C_{co}}(\mathbf{q_o}, \dot{\mathbf{q_o}}, \mathbf{q_c}, \dot{\mathbf{q_c}}) \dot{\mathbf{q_c}} + \mathbf{D}(\mathbf{q_o}) \dot{\mathbf{q_o}} \\ &\quad + \mathbf{g}(\mathbf{q_o}, \mathbf{q_c}) + \mathbf{b}(\mathbf{q_o}, \dot{\mathbf{q_o}}) = \mathbf{0} \end{aligned}$$

(2)

where

$$\begin{aligned}
 \mathbf{M}_c &= \begin{bmatrix} m_c & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & I_{c_z} \end{bmatrix} \\
 \mathbf{M}_o(\mathbf{q}_o) &= \begin{bmatrix} m_o r^2 & 0 \\ 0 & m_o \end{bmatrix} \\
 \mathbf{M}_{co}(\mathbf{q}_c, \mathbf{q}_o) &= \begin{bmatrix} -m_o r C_{\gamma\beta} & -m_o r S_{\gamma\beta} & m_o r^2 \\ -m_o S_{\gamma\beta} & m_o C_{\gamma\beta} & 0 \end{bmatrix} \\
 \mathbf{C}_o(\mathbf{q}_o, \dot{\mathbf{q}}_o) &= \begin{bmatrix} m_o r \dot{r} & m_o r (\dot{\gamma} + \dot{\beta}) \\ -m_o r (\dot{\gamma} + \dot{\beta}) & 0 \end{bmatrix} \\
 \mathbf{C}_{co}(\mathbf{q}_o, \dot{\mathbf{q}}_o, \mathbf{q}_c, \dot{\mathbf{q}}_c) &= \begin{bmatrix} 0 & 0 & m_o r \dot{r} \\ 0 & 0 & m_o r (\dot{\gamma} + \dot{\beta}) \end{bmatrix} \\
 \mathbf{D}(\mathbf{q}_o) &= \begin{bmatrix} d_\beta(r) r^2 & 0 \\ 0 & d_r(r) \end{bmatrix} \\
 \mathbf{g}(\mathbf{q}_o, \mathbf{q}_c) &= \begin{bmatrix} g m_o r S_{\gamma\beta} \\ -g m_o C_{\gamma\beta} \end{bmatrix} \\
 \mathbf{b}(\mathbf{q}_o, \dot{\mathbf{q}}_o) &= \begin{cases} \begin{bmatrix} 0 \\ -k_c(r - r_{\max}) - b_c \dot{r} \end{bmatrix} & \text{if } r \geq r_{\max} \\ \begin{bmatrix} 0 \\ k_c(r - r_{\min}) + b_c \dot{r} \end{bmatrix} & \text{if } r \leq r_{\min} \\ \begin{bmatrix} 0 \\ 0 \end{bmatrix} & \text{otherwise} \end{cases}
 \end{aligned}$$

- $\mathbf{M}_c$ represents the inertia matrix of the SCC. Note that it is considered diagonal and constant. Further details about this assumption can be found in Section 5;
- $\mathbf{M}_o(\mathbf{q}_o)$ represents the otoconium inertia matrix and it is diagonal since the otoconium is assumed to be a sphere whose mass is concentrated at its center (as stated above);
- $\mathbf{M}_{co}(\mathbf{q}_c, \mathbf{q}_o)$ represents the matrix that describes the coupling between the SCC and the otoconium accelerations meaning that the reference system of the SCC is not an inertial frame;
- $\mathbf{C}_o(\mathbf{q}_o, \dot{\mathbf{q}}_o)\dot{\mathbf{q}}_o$ and $\mathbf{C}_{co}(\mathbf{q}_o, \dot{\mathbf{q}}_o, \mathbf{q}_c, \dot{\mathbf{q}}_c)\dot{\mathbf{q}}_c$ describe the Coriolis and the centrifugal effects respectively which act on the otoconium and which are due to SCC motion and otoconium motion itself;
- $\mathbf{g}(\mathbf{q}_o, \mathbf{q}_c)$ is a generalized gravity force vector, i.e. the force vector $\mathbf{f}_g$ as expressed in polar coordinate.
- $\mathbf{b}(\mathbf{q}_o, \dot{\mathbf{q}}_o)$ describes the repulsive effects of the SCC walls by using a simple model that includes the wall's stiffness, k_c , and damping, b_c . The parameters k_c and b_c have been chosen by trial and error so as to obtain, in simulation, a reasonable system behavior when an impact occurs between the otoconium and the SCC wall;
- $\mathbf{D}(\mathbf{q}_o)$ describes the Stokes drag coefficients.

Concerning the $\mathbf{D}(\mathbf{q}_0)$ matrix, its elements can be defined as (Squires et al., 2004):

$$\begin{aligned}d_s &= 6\pi\eta\rho r_o \\ r_{mg} &= r_{min} + r_{gap} \\ r_{Mg} &= r_{max} - r_{gap}\end{aligned}$$

$$d_\beta(r) = d_s \quad (3)$$

$$d_r(r) = \begin{cases} d_s & \text{if } r_{mg} < r < r_{Mg} \\ d_s \frac{r_{gap}}{r - r_{min}} & \text{if } r_{min} \leq r \leq r_{mg} \\ d_s \frac{r_{gap}}{r_{max} - r} & \text{if } r_{Mg} \leq r \leq r_{max} \end{cases} \quad (4)$$

where $r_{gap} = 10^{-6}$ [m] (note that $r_{gap} < r_o$). In this way, the particle is free to slide along the SCC wall, as required by the therapeutic maneuvers which relies on otoconia sedimentation (Squires et al., 2004). In addition, the increasing value of the radial damping coefficient in the wall proximity is used to emulate adherence effects between the particle and the SCC wall. As previously stated, the value of the coefficient d_s is determined assuming that, from the point of view the hydrodynamic effects, the otoconium is a sphere whose radius is negligible with respect to the SCC cross section and that the radius of the SCC cross section is negligible with respect to the SCC curvature, $1/r_{mean}$.

Note that, during normal SCC functioning, an head movement causes the motion of the SCC fluid and a consequent deflection of the cupola (see Figure 1(a)). However, in canalithiasis, the very small time scale of the fluid inertial effects with respect to the otoconium's motion make such effects negligible in all those cases where just the otoconium's trajectory is of interest (Squires et al., 2004).

In addition, during manual RM, the otoconium's inertial forces could be considered negligible with respect to the gravitational force and to the Stokes drag. On the other hand, such effects are hereafter considered in order to allow the study of the SCC-particle relative motion along all the directions and to study possible particle-wall detaching maneuvers.

An important point to note is the particular structure of the dynamic eqs. (1) and (2). While the motion of the otoconium is influenced by the motion of the SCC, the vice-versa is not true thanks to the negligible mass of the otoconium with respect to the patient body. It follows that eqs. (1) and (2) are not cross-coupled, and that the motion of the SCC is independent. This means that only eq. (2) is necessary in order to compute the otoconium trajectory whenever the trajectory of the SCC is given (in terms of position, velocity and acceleration of all its three coordinates x , y and γ).

3.1 Manual unfeasible maneuvers: a case study

To show the effectiveness of maneuvers that exploit the rotation of the SCC along an axis passing through $\mathbf{O}_{SCC}$ and perpendicular to the $\mathbf{x}_B\mathbf{y}_B$ plane (Figure 5), a significant case study is considered.

The maneuver starts with the particle in the lower equilibrium point (at the bottom of the SCC, $\beta = -\pi/2$) and in contact with the wall, see Figure 6(b), and it can be conceptually divided in three phases:

1. A translational movement in the downward y direction, having high acceleration for a very limited amount of time (Figures 6(b) and 6(c)). It is assumed that an high inertial force can break the particle-wall interaction in case the otoconium is stuck to the SCC

Fig. 6. Otoconium radial trajectory during the rotational maneuver and details of the detaching phase.

soft tissue. At the time the otoconium is free to move within the SCC, it will tend to maintain its absolute position thanks to the particle own inertia and to a decreasing damping force (see eq. (4) as the particle-wall distance increases.

2. Simultaneously, the patient body is rapidly rotated backward of an angle of $\pi/2$ [rad] (Figure 7(c)). This rapid rotation causes the particle to remain almost in the same position with respect to the SCC, thanks to the Stokes drag force.
3. A rotation of the patient body at a particular speed $\dot{\beta}_{eq}$, that allows to maintain the particle in a floating condition by establishing an equilibrium between the gravity and the Stokes drag (Figures 7(d)-7(f)). This rotation is maintained until the otoconium has reached the ampulla. The motion stops with the patient in the normal sitting position ($\gamma = 2\pi$, see Figure 7(f) and Figure 7(b)).

In the example reported in Figure 6, the SCC is subjected to an acceleration of $3g$ in the $\mathbf{y}_B$ direction linearly decreasing to zero in 0.2 [s]. The final velocity along the $\mathbf{y}_B$ axis is slowly recovered to zero during the remaining part of the maneuver (steps 2 and 3).

Note that Hain et al. (2005) report a peak tangential acceleration exerted in the $\mathbf{x}_B$ direction (Figure 5) over 0.1 s during the Semont RM. The same authors claim that if there is clinical value to inertial forces acting on the otoconium, it would be most likely caused by breaking of canal-wall interactions and mobilizing an otoconium from the wall.

Assuming that the particle is located at the $r = r_{mean}$, the speed $\dot{\beta}_{eq}$ can be computed according to (Obrist & Hegemann, 2008; Squires et al., 2004) as:

$$\dot{\beta}_{eq} = \frac{|\mathbf{f}_g|}{d_{\beta}(r)r_{mean}} = \frac{m_o(1 - \rho/\rho_o)g}{6\pi\eta\rho r_o r_{mean}}$$

Fig. 7. Otoconium and SCC angular trajectory during the rotational maneuver.

Figure 6(a) shows the radial trajectory of the otoconium during the maneuver whereas Figure 7 reports the angular trajectory of SCC and particle. A detail of the first part of the trajectory is reported to highlight the detachment of the particle from the wall. Note that, during the remaining part of the maneuver, the radial position of the otoconium remains close to the SCC median radius (the oscillations are given by the uncertainties in the particle trajectory, especially during the detaching phase).

Moreover, the dynamic system (1)-(2) can be inverted so as to design the SCC trajectory (and, eventually, the necessary forces by means of (1)) when the desired otoconium trajectory $[\mathbf{q}_{o_d}, \dot{\mathbf{q}}_{o_d}, \ddot{\mathbf{q}}_{o_d}]$ is specified (where the subscript $_d$ stays for the desired trajectory instead of the actual one).

By inversion of eq. (2), the acceleration of the SCC can be then determined as:

$$\ddot{\mathbf{q}}_{c_d} = -\mathbf{M}_{co}^+(\mathbf{q}_{c_d}, \mathbf{q}_{o_d}) [\mathbf{M}_o(\mathbf{q}_{o_d}) \ddot{\mathbf{q}}_{o_d} + \mathbf{C}_o(\mathbf{q}_{o_d}, \dot{\mathbf{q}}_{o_d}) \dot{\mathbf{q}}_{o_d} + \mathbf{C}_{co}(\mathbf{q}_{o_d}, \dot{\mathbf{q}}_{o_d}, \mathbf{q}_{c_d}, \dot{\mathbf{q}}_{c_d}) \dot{\mathbf{q}}_{c_d} + \mathbf{D}(\mathbf{q}_{o_d}) \dot{\mathbf{q}}_{o_d} + \mathbf{g}(\mathbf{q}_{o_d}, \mathbf{q}_{c_d}) + \mathbf{b}(\mathbf{q}_{o_d}, \dot{\mathbf{q}}_{o_d})] \quad (5)$$

where $\mathbf{M}_{co}^+(\mathbf{q}_{c_d}, \mathbf{q}_{o_d})$ indicates the pseudo-inverse of the matrix $\mathbf{M}_{co}(\mathbf{q}_{c_d}, \mathbf{q}_{o_d})$. This last equation defines an ODE problem that can be easily solved numerically by double integration of (5) once the initial position/velocity of the SCC and the otoconium trajectory are known.

It is important to note that, since the $\mathbf{M}_{\text{co}}(\mathbf{q}_{\text{cd}}, \mathbf{q}_{\text{od}})$ is a 2×3 matrix, its null space can be defined as:

$${}^N\mathbf{M}_{\text{co}}(\mathbf{q}_{\text{cd}}, \mathbf{q}_{\text{od}}) = \text{Null} \{ \mathbf{M}_{\text{co}}(\mathbf{q}_{\text{cd}}, \mathbf{q}_{\text{od}}) \} = \begin{bmatrix} rC_{\gamma\beta} \\ rS_{\gamma\beta} \\ 1 \end{bmatrix} \quad (6)$$

Hence, the otoconium trajectory $[\mathbf{q}_{\text{od}}, \dot{\mathbf{q}}_{\text{od}}, \ddot{\mathbf{q}}_{\text{od}}]$ can also be achieved with a different choice of the SCC trajectory:

$${}^N\ddot{\mathbf{q}}_{\text{cd}} = \ddot{\mathbf{q}}_{\text{cd}} + {}^N\mathbf{M}_{\text{co}}(\mathbf{q}_{\text{cd}}, \mathbf{q}_{\text{od}})\lambda \quad (7)$$

where $\lambda \in \mathbb{R}$ is a suitable scalar coefficient used so as to select the desired SCC trajectory in the space of all the possible ones. The definition of the value of λ can be made on the base of different criteria. For instance the motion along a desired (penalized) direction can be minimized or the SCC center can be kept inside a desired region. It is worth reminding that (5) gives the minimum SCC acceleration that produces the desired otoconium trajectory.

4. Robotic chair kinematic design

Section 3 theoretically proves that particular RM could be used in order to firstly detach otoconia possibly stuck to the SCC's walls and then to drive them out of the canals while preventing further interactions with the canals' soft tissues. These particular RM require a rotation of an SCC along an axis passing through the point $\mathbf{O}_{\text{SCC}}$ and perpendicular to the $\mathbf{x}_{\text{B}}\mathbf{y}_{\text{B}}$ plane (Figure 5).

Therefore, starting from the experience of Nakayama & Epley (2005) and on the basis of the aforementioned considerations, the aim of this section is to define the kinematic structure of a serial robot which could add more flexibility in the execution of manually unfeasible RM when compared to existing solutions (e.g. the OPS or human-carrying industrial robots). In particular, the novel kinematic structure should be capable of practically applying the RM proposed in Section 3 to each one of the six SCC.

In summary, the considered serial linkage complies with the following general specifications:

- Capability to perform all existing RM based on otoconia sedimentation;
- Capability to perform unlimited rotations along the revolution axis of every SCC conceived hereafter as a circular toroid;
- Capability to apply controlled inertial forces on every SCC (similarly to the inertial forces applied during the Semont RM for treating the PC);
- Capability to reach a position where the moving chair would be easily accessible.

Other important issues are the safety and the ergonomics requirements as well as the overall dimensions that must be acceptable for usage in a hospital environment. Moreover, the psychological impact of these kind of machines on the elderly does not have to be undervalued. To this respect, a closed structure (like in Figure 4) has been discarded preferring the use of a serial manipulator. Despite the fact that serial structures are less rigid (and therefore less accurate), they dispose of a better workspace, better accessibility and are more "acceptable" by the patient in terms of human-robot interaction and user friendliness.

On the other hand, the adoption of commercial manipulators, alike an anthropomorphic robotic arm (Kuka, 2004), has been excluded as long as those structures do not guarantee the desired degree of flexibility. In fact, the existence of joints' limits and possible self collision

highly restricts the feasible rotations along the SCC revolution axis (as it can be proven by solving the inverse kinematic problems for such kind of manipulators). Therefore, differently from the conceptual design of a "general purpose" manipulator, it is necessary to kinematically design an "on-purpose" machine capable of complying with the aforementioned specifications.

Precisely, the topological and dimensional synthesis of the serial linkage has been achieved by means of a simplified Task Based Design (TBD) technique (Kim, 1992).

As previously proposed in the literature (Chedmail & Ramstein, 1996; Chen & Burdick, 1995; Kim & Khosla, 1993a; Yang & Chen, 2000), the TBD technique makes use of Genetic Algorithms (GA) (Goldberg, 1989) in order to determine a robot's kinematic structure which is capable of performing a given set of tasks. The robot's features to be determined include minimum number of degrees of freedom (MDOF), topology, and Denavit-Hartenberg parameters. For instance, TBD has been proven effective in determining assemblies of modular robots optimally suited to perform a specific assignment. In the contest of modular assemblies, both the topology of the serial chain and the links' length must be treated as non continuous variables. Hence, it is necessary to use an optimization method, such as the GA, which is capable of dealing with both highly nonlinear functions and discrete variables. In general, the optimization problem itself can be posed as unconstrained (as in Chedmail & Ramstein (1996)) or constrained (as in Kim & Khosla (1993a)). In the latter case different constraints can be applied e.g. reachability, joint limits, obstacle avoidance, dexterity measures. In the same way, the objective function to be optimized can be chosen in different manners such as workspace maximization, manipulability index maximization, degrees of freedom (DOF) minimization, mechanical constructability minimization. In this respect, global methods, as opposed to progressive ones, try to accomplish an optimum design in one step only by minimizing a weighted sum of the different requirements.

Similarly to the aforementioned example concerning modular robots, the optimization process presented hereafter deals with discrete variables (i.e. manipulator topology and discretized D-H parameters, see Section 4.2). The algorithm makes use of a progressive method which meets consecutive constraints and successive optimized solutions. Note that the robot kinematic design can be further improved by using a continuous optimization method (Avilés et al., 2000) once a possible robot's topology has been finalized.

4.1 Specification of tasks

In order to apply TBD techniques, a series of tasks must be specified analytically. For this purpose, three coordinate systems need to be defined (see Figure 8) as follows:

- $(xyz)_B$, an absolute frame attached to the ground;
- $(xyz)_{CoG}$, attached to the Center of Gravity (CoG) of the patient plus the moving chair, hereafter considered as a rigid body: $+z_{CoG}$ (the *yaw* or *horizontal rotation* axis) is a vertical axis pointing up, $+x_{CoG}$ (the *roll* axis) is perpendicular to $+y_{CoG}$ and $+z_{CoG}$ pointing anteriorly, and $+y_{CoG}$ (the *pitch* axis) points out the left ear;
- $(xyz)_{SCC}$ located on the intersecting point of the three revolution axes of each toroid, here considering left SCC only. z_{SCC} lies on the axis of the HC, y_{SCC} lies on the axis of the PC, x_{SCC} lies on the axis of the AC. SCC are considered as mutually orthogonal.

Another coordinate system attached to right SCC can be defined in the same manner.

As previously stated (Figure 1(b)), the AC lies on a plane inclined approximately 45° with respect to sagittal plane $(xz)_{CoG}$, the PC lies on a plane inclined 45° but in opposite direction and the HC is perpendicular to the other two canals and inclined approximately $15-20^\circ$ with

Fig. 8. Reference frames (solid lines) and relative homogeneous transformations (dotted lines).

respect to the horizontal plane $(xy)_{CoG}$. The desired trajectories that fulfill the requirements of the kinematic specifications are described by a finite set of tasks given as homogenous transformation matrices between $(xyz)_B$ and $(xyz)_{CoG}$. In the remaining part of the chapter the notations $R_x(\cdot)$, $R_y(\cdot)$ and $R_z(\cdot)$ will be used to address 3×3 rotational matrices with respect to x -, y - and z -axis respectively whereas $\bar{R}_x(\cdot)$, $\bar{R}_y(\cdot)$, $\bar{R}_z(\cdot)$ address the 4×4 homogeneous matrices associated with those same rotations.

Task set 1 – Rest position. This set contains only one task that depicts the chair in a position which can be easily reached by the patient. The task is described by the following homogeneous matrix:

$$T_{1,1} = \begin{bmatrix} R_z(90^\circ)R_y(45^\circ) & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (8)$$

where h indicates the desired CoG height from the ground.

Task set 2 – Eccentric rotation. This set contains all the tasks that describe an eccentric rotation with variable radius.

$$T_{2,i} = \begin{bmatrix} R_y(-20^\circ)R_z(-\theta_i) & \rho \sin(\theta_i) \\ \rho \cos(\theta_i) & h \\ 0 & 0 \\ 0 & 1 \end{bmatrix} \quad (9)$$

where ρ is the radius of the circular trajectories, $T_{2,i}, i = 0 \dots N - 1$ are N tasks describing circular trajectories while maintaining the HC plane parallel to the ground, and $\theta_i \in \{\frac{\pi}{2N}i\}$ for $i = 0, \dots, N - 1$. Eccentric rotations can be used in order to apply controlled inertial forces

on the HC (similarly to the stimuli arising during the Semount RM for PC treatment).

Task set 3 – Existing clinical maneuvers. This task set collects the homogeneous matrices describing existing manual maneuvers. These maneuvers (Boniver, 1990) can be considered as a set of rotations along $(xyz)_{CoG}$ – axis. For instance, the task set that describes the Dix-Hallpike maneuver is given by the union of two concatenated subset with $N/2$ tasks each. The two subsets are described by the following matrices:

$$\mathbf{T}_{3,i}^{(1)} = \begin{bmatrix} & \mathbf{R}_z(\theta_i) & & 0 \\ & & & 0 \\ 0 & 0 & 0 & h \\ & & & 1 \end{bmatrix} \quad (10)$$

$$\mathbf{T}_{3,i}^{(2)} = \mathbf{T}_{3,(N-1)/2}^{(1)} \begin{bmatrix} & \mathbf{R}_y(\theta_y) & & 0 \\ & & & 0 \\ 0 & 0 & 0 & 1 \\ & & & 1 \end{bmatrix} \quad (11)$$

where $\theta_i \in \{-\frac{\pi}{2N}i\}$ and $\theta_j \in \{\frac{3\pi}{2N}j\}$ for $i, j = 0, \dots, \frac{N-1}{2}$.

Task set 4 – Rotation along SCC axis. Task set 4 creates a circular path of $(xyz)_{CoG}$ around the revolution axis of each SCC. Consider left SCC first. Starting from $(xyz)_{CoG}$ in rest position, let us define:

$$\mathbf{P}_2 = \begin{bmatrix} 1 & 0 & 0 & \Delta p_{left,x} \\ 0 & 1 & 0 & \Delta p_{left,y} \\ 0 & 0 & 1 & \Delta p_{left,z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (12)$$

$$\mathbf{P}_3 = \begin{bmatrix} \mathbf{R}_x(\Omega_{HC})\mathbf{R}_z(\Omega_{AC}) & \mathbf{0}_{3 \times 1} \\ \mathbf{0}_{1 \times 3} & 1 \end{bmatrix} \quad (13)$$

where $\Delta \mathbf{p}_{left} = \mathbf{O}_{SCC_{left}} - \mathbf{O}_{CoG} = [\Delta p_{left,x} \ \Delta p_{left,y} \ \Delta p_{left,z}]^t$ is the vector that identifies the position of $xyz_{SCC_{left}}$ with respect to the patient's body frame, $\mathbf{O}_{SCC_{left}}$ and $\mathbf{O}_{CoG}$ are the origins of $(xyz)_{SCC}$ and $(xyz)_{CoG}$ respectively, Ω_{HC} and Ω_{AC} are the orientations of HC and AC defined as rotations along $(xyz)_{CoG}$ $\mathbf{P}_2$.

Let us define the following matrix as a design parameter :

$$\mathbf{P}_{BO} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & h + \Delta p_{left,z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (14)$$

The rotations along the AC, HC and PC axis are respectively given by:

$$\text{AC : } \mathbf{T}_{4i} = \mathbf{P}_{BO} \bar{\mathbf{R}}_x(\theta_i) (\mathbf{P}_2 \mathbf{P}_3)^{-1} \quad (15)$$

$$\text{HC : } \mathbf{T}_{5i} = \mathbf{P}_{BO} \bar{\mathbf{R}}_y(\pi/2) \bar{\mathbf{R}}_z(\theta_i) (\mathbf{P}_2 \mathbf{P}_3)^{-1} \quad (16)$$

$$\text{PC : } \mathbf{T}_{6i} = \mathbf{P}_{BO} \bar{\mathbf{R}}_z(\pi/2) \bar{\mathbf{R}}_y(\theta_i) (\mathbf{P}_2 \mathbf{P}_3)^{-1} \quad (17)$$

where $\theta_i \in \{2\pi i\}$ for $i = 0, \dots, N$.

Supposing a perfect symmetry of the SCC canals with respect to the body's sagittal plane, the tasks concerning the right SCC can be obtained by setting

$$\Delta \mathbf{p}_{right} = \begin{bmatrix} \Delta p_{left,x} & -\Delta p_{left,y} & \Delta p_{left,z} \end{bmatrix}^T \quad (18)$$

At this stage, some design decisions have already been made:

- $(\mathbf{xy})_{\mathbf{B}}$ rest position and patient orientation could be left free under certain limits, whereas $\mathbf{T}_{11}$ specifies a patient positioned over $(\mathbf{xyz})_{\mathbf{B}}$ origin with a given orientation.
- There is no need to request a certain orientation along $\mathbf{z}_{\mathbf{CoG}}$ as the initial pose for the set of existing manual RM whereas $(\mathbf{xy})_{\mathbf{B}}$ and $(\mathbf{xy})_{\mathbf{CoG}}$ are requested to be aligned as Task set 3 starts.
- The maneuvers in Task set 4 are conceived as rotations along a revolute pair with height $h + \Delta p_{left,z}$ from the ground when each set of rotations along each SCC could be exploited with different R-joints and in different spatial positions.

4.2 Problem Statement and Data Structures

The determination of the kinematic parameters for an optimized open-chain manipulator can be regarded as a generic optimization problem: minimize $\mathbf{f}(\mathbf{X})$, $\mathbf{X} \in \mathbf{S}$, where $\mathbf{S}$ is the search space of possible solution points, subjected to a certain number of constraints.

Because of the high-dimensioned parameter space, an heuristic algorithm based on the theory of GA has been implemented in order to find a possible solution. Within GA terminology, the objective function to be optimized, $\mathbf{f}(\mathbf{X})$, is called *fitness function*, whereas an instance of a possible solution $\bar{\mathbf{X}}$ is called *individual*. The set of all the possible solutions at a given iteration of the algorithm is called *population*. Let us define:

$$\mathbf{X} = \begin{bmatrix} \mathbf{T}_0^B & \mathbf{0}_{4 \times 1} \\ \mathbf{DH} & \mathbf{type} \\ \mathbf{T}_{tool}^n & \mathbf{0}_{4 \times 1} \end{bmatrix}, \quad \text{where : } [\mathbf{DH} \quad \mathbf{type}] = \begin{bmatrix} \alpha_1 & a_1 & \vartheta_1 & d_1 & R \text{ or } P \\ \alpha_2 & a_2 & \vartheta_2 & d_2 & R \text{ or } P \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & F \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \alpha_n & a_n & \vartheta_n & d_n & R \text{ or } P \end{bmatrix} \quad (19)$$

where $\mathbf{X}_{(n+8) \times 5}$ is a matrix representation of a serial robot, n is its number of DOF, $\mathbf{T}_0^B$, $\mathbf{T}_{tool}^n$ are 4×4 homogenous matrices, $[\mathbf{DH} \quad \mathbf{type}]_{n \times 5}$ is an augmented matrix of D-H parameters with an appended column indicating joint type. D-H parameters are listed as follows: $[\alpha, a, \vartheta, d]$.

Possible joints are 1-DOF joints (revolute (R) or prismatic (P)) and 0-DOF joints used as a slack variable (F) to model a manipulator with less DOF than the maximum allowed.

According to the Denavit-Hartenberg (D-H) convention, $\mathbf{T}_0^B$ and $\mathbf{T}_{tool}^n$ indicate position and orientation of robot base and tool with respect to the coordinate system attached to the first and last movable joints respectively. Considering robot tool position coincident with the origin of $(\mathbf{xyz})_{\mathbf{CoG}}$ means that just the orientation part of $\mathbf{T}_{tool}^n$ needs to be specified. The links' length is described as a discrete variable varying from zero to a predefined maximum value and then divided into a finite number of parts. If the i -th joint is a revolute pair then ϑ_i is a pose variable and therefore not considered as a design parameter, if joint i -th is prismatic then d_i is the pose variable. Finally, if i -th joint is fixed, the corresponding row will be deleted in the evaluation process.

The candidate robots generation is based on a set of heuristic rules similar to those found in (Kim & Khosla, 1993a):

- **Kinematic simplicity:** α and ϑ (whenever the latest is considered as a design variable) can assume values belonging to the set $[0, \pm\pi/2, \pi]$. Concerning R-joints, at least one of the two variables representing length (a, d) is set to zero.
- **Redundancy avoidance:** R-joints described by D-H parameters of the type $[0, 0, \vartheta, d]$ cannot be followed by another R-joint, thus avoiding solutions where two revolute joints are mounted on the same axis.

4.3 Evaluation Procedure

The design process of the serial link chain is automated through an optimization procedure which allows a less subjective decision making progression and increases the performance with respect to an objective function defined in order to assess the benefit of a solution (Figure 9).

The type of searching method depends most of all on the type of variables to be dealt with (continuous, discrete or mixed) and on the type of problem (constrained or unconstrained). In this chapter, a GA is used to solve a constrained optimization process on the discrete variable. Exhaustive search techniques, which basically measures the benefit of each possible individual, could be used to find the exact optimal solution; whether this technique would be better suited for a specified problem is just a matter of computational time. Probabilistic search techniques, such as GA or simulated annealing, become a good choice when the search space is extremely large.

At each step a GA creates a new population of individuals using the individual or data structures of the current generation. It basically scores each current individual computing its fitness value; it then selects a set of parents based on their fitness (selection process) and produces a new generation starting from this given set of individuals. Individuals of the new generation are either taken from the selected parents without any change (elitism), randomly changing a single parent (mutation) or combining vector entries of different parents within the same class of substructures (i.e. avoiding as a result an individual with different data structure from the one reported). The algorithm stops when a given stopping criteria is met. In this chapter the only specified criteria is a limit on the number of generations.

Given a set of tasks, it is stated that a reachability constraint (RC) must be satisfied. For a particular task, the RC is said to be satisfied if: 1) There exists a solution of the inverse kinematic problem (IK) which presents a positional error norm and an orientational error norm lower than an appropriate threshold (Kim & Khosla, 1993b) 2) Such solution is found within a certain number of iterations. As long as the structure of the manipulator is not yet defined and the serial chain can assume a very high number of configurations, a numerical method to solve the IK problem is used; reference is made to the singularity robust IK method proposed by L. Kelmar and P. K. Khosla (Kelmar & Khosla, 1990). If the RC is not satisfied the fitness value is set to a very large number.

4.4 Design stages

The GA-based optimization procedure has been splitted in two different stages (Figure 9).

4.4.1 Minimized Degrees-of-Freedom approach (MDOF)

In the first design stage the fitness value is simply the number of DOF of the manipulator regardless of joints being revolute or prismatic. IK is computed for every task in series on

Fig. 9. Design steps and evaluation procedure.

structures where rows concerning fixed joints are previously deleted. If the RC is not satisfied the fitness value is set to a very large number and successive tasks are not evaluated. Prior to IK calculation, which is the most time consuming procedure, it is verified that:

$$r_i - \sum_{j=0}^n l_j < 0 \quad i = 1, \dots, N_{TOT} \quad \text{where} \quad \begin{cases} l_j \leq L_{\max} & \text{if } j\text{-th joint is revolute} \\ l_j = 2L_{\max} & \text{if } j\text{-th joint is prismatic} \end{cases} \quad (20)$$

where N_{TOT} is the total number of tasks, r_i is the Euclidian distance of i -th task from the robot base and l_j is j -th link length. $l_0 = \|\mathbf{O}_0 - \mathbf{O}_B\|$ ($\mathbf{O}_0$ and $\mathbf{O}_k$ are supposed coincident, where $\mathbf{O}_k$ is the origin of $(\mathbf{xyz})_k$ according to Chocron & Bidaud (1997)). After IK, i -th RC is considered not satisfied if:

$$\sqrt{a_j^2 + (\Delta d_{j,\max}^2)} > 2L_{\max} \quad (21)$$

where $\Delta d_{j,\max} = |d_{j,\max} - d_{j,\min}|$ (i.e. during motion the prismatic joint has traveled a distance greater than $2L_{\max}$, its initial length being set to a_j).

The result of this design step is the minimum number of DOF necessary to perform task specifications meaning that the algorithm has found an individual $\bar{\mathbf{X}}$ that represents a n -DOF kinematic structure able to perform every pose.

4.4.2 Mechanical Constructability Minimization.

The aim of this second design stage is the minimization of total link length and therefore of total robot's mass. The fitness function is set to:

$$F(X) = \sum_{j=0}^n l_j, \quad \text{where} \quad \begin{cases} l_j = \sqrt{a_j^2 + d_j^2} & \text{if } j\text{-th joint is revolute} \\ l_j = \sqrt{a_j^2 + (\Delta d_{j,\max}^2)} & \text{if } j\text{-th joint is prismatic} \end{cases} \quad (22)$$

Fig. 10. Schematic representation of the best solution founded via GA optimization: revolute and prismatic joints are depicted as cylinders and boxes respectively.

At this design stage fixed joints are not allowed and must be removed before the procedure can start.

4.5 Simulation Results

The algorithm is implemented using the Matlab Genetic Algorithm and the Direct Search Toolbox. RobotiCad Toolbox for Matlab (Falconi & Melchiorri, 2007; Falconi et al., 2006) has been used as IK solver and visualization tool.

Simulations are run for a population size of 50 individuals-200 generations. For a given task, the implemented IK solver fails if the number of iterations exceeds 500 or succeeds if both positional and orientational error norms are lower than 10^{-3} . Table 2 reports task specification parameters. Fitness value for not feasible structures was set to 9 during the first design stage and to 100 during the second one.

Symbol	Δp_{left} [m]	Ω_{HC}	Ω_{AC}	h [m]	L_{max} [m]	α [rad]	N_{TOT}	ρ [m]
Quantity	$\begin{bmatrix} 0.1 \\ 0.1 \\ 0.75 \end{bmatrix}$	20°	45°	0.75	2	$[0, \pm\pi/2, \pi]$	76	0.5 – 1

Table 2. Input Variables

	α [rad]	a [m]	ϑ [rad]	d [m]	R/P
Joint 1	$\pi/2$	0.00	ϑ_1	1.20	R
Joint 2	$3\pi/2$	0.10	ϑ_2	0	R
Joint 3	$3\pi/2$	0.00	π	d_3	P
Joint 4	$3\pi/2$	0.00	ϑ_4	0	R
Joint 5	$3\pi/2$	0.00	ϑ_5	0.20	R
Joint 6	π	0.00	ϑ_6	0	R

Table 3. Best solution’s Denavith-Hartenberg parameters and joint types.

The best found solution is reported in Table 3, the matrices $\mathbf{T}_0^B$ and $\mathbf{T}_{tool}^n$ being two identity matrices i.e. the absolute frame and the robot’s base frame are coincident and the frame attached to the last link is coincident with the robot’s tool frame. The solution’s representation is depicted in Figure 10. The proposed serial linkage is topologically similar to a Stanford manipulator presenting a particular wrist (not spherical). As long as no obstacle avoidance has been considered, the only useful information that can be found by the MDOF approach is that the specified set of tasks could not be accomplished by less than 6-DOF robots or that the GA couldn’t find such solution applying the given set of heuristic rules (*mechanical simplicity and redundancy avoidance*).

A conceptual design of the six-DOF robot (patented by Berselli et al. (2007)) is depicted in Figure 11(a) whereas Figure 11(b) shows the manipulator performing a rotation along the revolution axis of the right AC.

In particular, the last two joints are used to replicate every existing manual maneuver and the first joint is used to apply controlled inertial forces (similar to the stimuli arising during the Semount RM) on the HC via eccentric rotation of the patient. The other DOF are used to control the trajectory of the otoconia within an SCC performing full rotation along the revolution axis of every SCC (as shown in Section 3). At this stage no care was taken concerning dynamic and structural analysis and optimization. Further steps for the development of a working prototype include decision making of possible motors, gears, bearings and couplings as well as cabling and material selection.

5. Discussion and future work

Given the manipulator’s kinematic model reported in Tab. 3, the movements of the SCC and of the patient body can be easily related to the motion of the manipulator. In particular, the dynamic model of eqs. (1) and (2) allows the study of the otoconium movements during maneuvers that can be potentially performed by the proposed serial linkage. In fact, the chosen kinematical structure allows to achieve unlimited rotations along the revolution axis of every SCC and to control the SCC planar movement in the x and y directions (Figure 5). Obviously, this kind of RM cannot be manually achieved.

Fig. 11. Manipulator performing tasks.

Note that the choice of suitable strategies for controlling the manipulator (Siciliano & Khatib, 2008) makes it possible to assume that the dynamics of the patient's body movements is described by eq. (1). Therefore, $\mathbf{M}_c$ can be assumed to be the identity matrix. This assumption implies that all the spurious effects that deviate the behavior of the SCC dynamics with respect to eq. (1) must be compensated by the manipulator controller.

It is clear that the otoconium trajectory must be carefully selected in order to achieve a SCC motion that: 1) It is tolerable by the patient (in terms of imposed acceleration); 2) It does not overcome the manipulator limits (in terms of possible pose and velocity/acceleration).

At last, it should be pointed out that eq. (1) is useful when determining the forces which are necessary to accomplish a given RM once the otoconium trajectory and the patient parameters are known.

6. Conclusions

This chapter proves the usability of a simplified Task Based Design technique as an aid in the synthesis of serial linkages and presents a novel robotic chair to be used in diagnosing and treating BPPV. The specification of the tasks to be performed by the chair has been based upon direct specifications given by well-trained doctors or upon the observation that BPPV therapy could be improved once the limits of the manual maneuvers are overcome. Supposing that it is possible to control the motion of a SCC along a plane perpendicular to the SCC revolution axis, an idealized BPPV's dynamic model has been used to show that manually unfeasible maneuvers can be optimized for better treating positional vertigo.

Therefore, as a response to a series of new requirements, the presented novel robotic chair is capable of performing both existing manual maneuver based on otoconia sedimentation and unlimited rotations along the revolution axis of every SCC while controlling the SCC planar motion.

To the best of the author's knowledge, the proposed solution kinematically differs from any existing device and could be used to enhance the rate of success of BPPV non-invasive therapies.

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This book presents the most recent research advances in robot manipulators. It offers a complete survey to the kinematic and dynamic modelling, simulation, computer vision, software engineering, optimization and design of control algorithms applied for robotic systems. It is devoted for a large scale of applications, such as manufacturing, manipulation, medicine and automation. Several control methods are included such as optimal, adaptive, robust, force, fuzzy and neural network control strategies. The trajectory planning is discussed in details for point-to-point and path motions control. The results in obtained in this book are expected to be of great interest for researchers, engineers, scientists and students, in engineering studies and industrial sectors related to robot modelling, design, control, and application. The book also details theoretical, mathematical and practical requirements for mathematicians and control engineers. It surveys recent techniques in modelling, computer simulation and implementation of advanced and intelligent controllers.

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