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Synthesis of Prosthesis Architectures and Design of Prosthetic Devices for Upper Limb Amputees

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1. Introduction

This chapter presents a procedure for the Determination of the Optimal Prosthesis Architecture for upper limb amputees (DOPA). The presented approach can consistently manage both the clinical aspects and the technical issues involved in the design of electromechanically actuated prostheses. The procedure is composed on one hand of algorithms useful for analyzing the patients' requirements and on the other hand of algorithms that perform kinematic and kinetostatic simulations of several architectures of artificial arms attempting to fulfil important activities of daily living. The systematic evaluation of the prosthesis models' performance can methodically guide designers in the synthesis of the optimal prosthesis that best suits the patients' requirements.

1.1 Prosthetic rehabilitation of upper limb amputees

The loss or the congenital deficiency of an upper limb part represents a serious physical and psychological trauma, apart from having an evident and considerable restriction on personal autonomy in everyday living. Rehabilitating an amputee with a proper device allows the patient to recover (part of) the lost autonomy and the sense of psychophysical integrity, and thus to enable his/her reintegration in domestic, working and social environments.

The prosthetic intervention is a complex process which involves technical aspects and clinical issues strictly dependent on the amputee to be treated; prosthetic rehabilitation is therefore carried out by a multidisciplinary team including physicians, technicians, therapists and psychologists which operates with the aim of providing the amputee with the device and the services that best match his/her different requirements. The first step the rehabilitation team must face is to investigate the individual needs of every amputee. The choice of the best prosthesis for a given patient depends on several aspects, all of which must be taken into account (Atkins & Meyer, 1989):

- amputation level
- mono- or bi-laterality of the amputation
- patient's age
- patient's gender
- stump conditions (shape, muscle strength, skin conditions, pain…)
- range of motion of the residual limb

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- presence of other diseases
- personal motivations for rehabilitating and expectations regarding the prosthesis
- psychological status
- home environment and family support
- subject's particular characteristics
- …

Even if it is glaringly obvious that the evaluation of these aspects is strictly patient-dependent, it is generally possible to state that for mono-lateral amputees the sound limb becomes dominant and the prosthesis works mainly as an auxiliary device for bimanual activities. On the contrary, for bilateral amputees the prostheses are strictly necessary to perform those activities of daily living that allow the patient not to be completely dependent on others' help thanks to the acquisition of a certain level of functional autonomy. Obviously, the higher the level of amputation the greater the importance of the prosthetic devices. The right selection of the proper prosthesis for a given patient relies on the assessment of the patient's characteristics and must be made by experienced personnel.
In order to satisfy the patient's needs the features that a prosthesis must have are:

1. the highest possible dexterity
2. good performance (in terms of velocity and forces/torques)
3. appropriate robustness
4. efficient control
5. a humanlike appearance
6. a light weight
7. proper size and proportions
8. good comfort for the wearer
9. easy control for the amputee
10. extremely reliable components of the artificial system
11. a low noise level
12. sufficient autonomy of the energy source to allow the prosthesis to work all day

It is possible to summarize the features required of a prosthesis as good *functionality* of the artificial arm on one hand (features 1–4) and good *wearability* for the patient on the other (features 5–9). The last specifications, 10 to 12, concern technological issues and the level of their observance depends basically on the component design, the materials used and the state of the art of both the electronic and the mechanical fields. It is worth noting that functionality and wearability are basically contrasting features; for instance, a device which has to provide high forces and speed must supply an appropriate power, implying a size of actuators far from lightweight. When selecting the appropriate prosthesis for a given amputee, the importance to be allocated to every single factor strictly depends on the evaluation of the patient's characteristics and requirements.

1.2 Upper limb prostheses

There are various kinds of prosthesis to be evaluated and chosen from. The "externally powered prosthesis", i.e. a robotic arm where the artificial limb segments are driven by electromechanical joints, is the most advanced. The joint motors are directly activated by the amputee by means of input commands that are collected by specific sensors located in the socket of the prosthesis, the socket being the interface by means of which the prosthesis is suspended on the patient's stump. The command signals are

processed by a programmable electronic circuit which carries out the control strategy to operate the device. Rechargeable batteries power all these components. Some passive friction joints are sometimes included in the system and are useful to give the prosthetic limb an optimal pre-determined configuration when performing certain tasks. The passive joints are operated by applying external forces by means of the sound limb or resting the artificial segments on fixed points, before or after the action of the active joints.

Currently, the most common electromechanical prosthetic components available on the market are many kinds of terminal devices (each with one degree of freedom – DoF – for grasping), the elbow joint, the wrist prono-supination unit (which allows the terminal device to rotate around the longitudinal forearm axis), and the wrist flexion unit. Many other active articulations have been studied and proposed as prototypes but they have not yet been distributed commercially. Among the recent interesting research results, the authors would like to mention: the multi-fingered prosthetic hands (Kyberd et al., 2001; Pons et al., 2004; Yang et al., 2004), which provide the terminal device with more than one DoF, thus making different grip patterns available (one of these seems ready to be commercialized[1]); a powered humeral rotator (Weir & Grahn, 2005) which allows the forearm segment to rotate around the longitudinal humeral axis (this is a novelty, because most above-elbow prostheses are equipped with passive humeral rotators); a shoulder joint with one DoF for upper arm elevation (Gow et al., 2001); a shoulder joint with two DoFs which is based on a differential mechanism and provides upper arm elevation and abduction (Cattaneo et al., 2001).

There are several ways of controlling electrically-powered prostheses, the most popular being myoelectric control: electromyographic signals (EMG, i.e. electrical signals associated with the muscle contractions), measured on the skin by myoelectric electrodes located in the socket, are properly amplified and filtered, and then processed by the controller that switches the motors on or off in the active joints to produce movements and functions. Although theoretically possible, the *simultaneous and independent* contraction of distinct bundles of muscles, that would generate EMG signals able to operate different functions at the same time is very difficult and stressing for the patient. The myoelectric control scheme is therefore generally based on the sequential activation of the prosthetic articulations one at a time, resulting in a not very natural control. In this context, some recent results seem to be promising to overcome this limitation (Kuiken et al., 2004).

The good qualities of this prosthesis are sufficient functionality, good performance and a pleasant appearance. The critical aspects are the weight and the volume of the physical structure, and the intricate control, due to the sequential activation of both the active and passive joints. Finally, it is proven that electrically-powered prostheses provide a high level of technology but at a high cost.

1.3 New prosthesis design and overview of the presented method

In order to provide high level disarticulated patients with a comfortable, humanlike and user-friendly prosthesis, not all the physiological joint movements can be replicated, thus limiting the functionality of the artificial arm. When compared to the human arm, the

[1] http://www.touchbionics.com/page.php?pageid=12&section=3.

dexterity of current commercial prostheses is very poor and amputees generally have to resort to compensatory movements of the residual limb, or even of other parts of the body as well as to auxiliary aids to execute many motor tasks. For patients with very high level amputations (bilateral above all), who have an extremely restricted residual movement ability, current prostheses could be inadequate to guarantee the functionality needed to reach a satisfactory level of autonomy. In order to solve this deficiency and to improve the quality of life of this amputee population, the development of new electrically powered prostheses with greater mobility, advanced control and good "wearability" is thus required.

It is authors' firm belief that the same observations that guide the rehabilitation team in the selection of the proper device for a given patient must also be considered by engineers and technicians when designing new prosthetic devices. Computer-based simulations represent a useful tool, in this perspective, for the development of new mechanical systems. In particular, the work presented in (Romilly et al., 1994) shows how the kinematic simulations of artificial arm models attempting to execute given trajectories can guide the development of powered orthoses with less than six DoF.

This chapter presents a methodology for the synthesis of new prosthetic architectures for patients with high level amputation, based on a procedure for the determination of the best compromise between the contrasting features required of a prosthesis, taking into account the different needs of diverse patient profiles. "Architecture" is intended here as the geometry and the topology of a robotic arm model, i.e. the number and type (active/passive) of its joints and their arrangement.

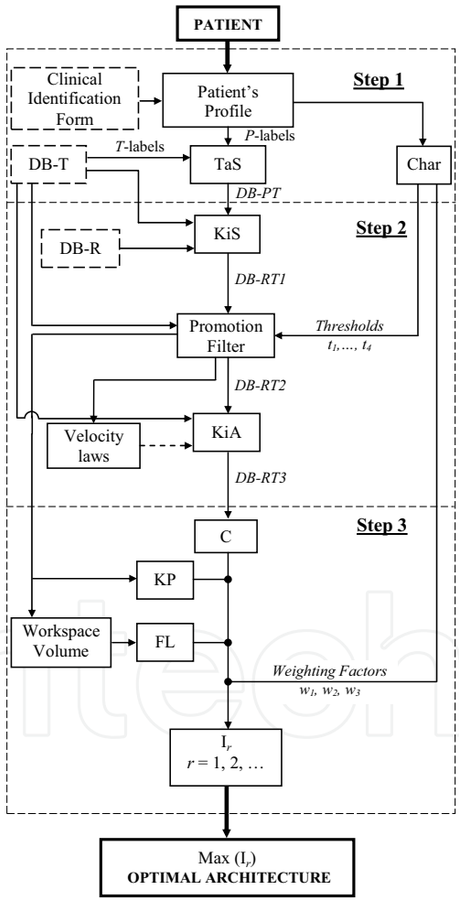
With the proposed procedure, the characteristics, the needs and the goals of a generic patient are formalised and organised in such a way as to be systematically analysed by means of specifically developed algorithms. Based on the collected data, further algorithms then perform the kinematic and kinetostatic simulations of several robotic arm architectures with one up to six active joints differently arranged (and considering the possible presence of passive joints as well) when carrying out some activities of daily living considered important for a given amputee. The models with less than six DoF correspond to simpler robot architectures and are thus appreciated from the wearability viewpoint; on the other hand, their performance is poorer than those of the six DoF models, because they normally carry out the manipulation tasks with an error which increases as the number of active joints decreases. The structure simplification of these robots and the corresponding worsening of their global functionality are evaluated with respect to the quality of life assigned to the patient profile. For this purpose, some indices have been specifically developed to properly weigh up both the clinical aspects (depending on the patient) and the technical factors (depending on the robotic models).

The approach is subject-oriented, foreseeing a single patient as input and providing his/her optimal prosthesis as output. However, the final application of the methodology can supply more general design guidelines, suitable to determine a limited number of prosthesis architectures able to match the requirements of many different amputees.

Finally, the results of the kinematic and kinetostatic simulations can provide the mechanical design specifications (e.g. the joint range of motion, the power of the actuators) of the new devices that will prove fundamental in overcoming the limitations of the existing prostheses.

2. The DOPA procedure

The procedure receives a given patient's information as input and provides his/her corresponding optimal prosthesis model as output (Fig. 1). It is based on a database and a number of algorithms which make it possible to choose the optimal robot arm architecture able to fit patient's *specific* needs and limitations. On one hand the database (database *DB-T*) collects upper limb activities of daily living and the corresponding trajectories which model them – hereinafter "Reference Trajectories", normally requiring six DoF for positioning and orienting tasks – and on the other hand (database *DB-R*) several kinematic models of upper limb prostheses with one up to six active revolute joints differently arranged and possible revolute or spherical passive joints (Fig. 3). The procedure can be considered as a process of three sequential steps, running automatically once that the appropriate amputee data have been entered.



Abbreviation	Meaning
T-labels	Markers of motor tasks
P-labels	Markers of the patient profile
DB-T	Upper Limb Activities Database
TaS	Task Selection Algorithm
DB-PT	Upper Limb Activities selected for the patient
Char	Characterization Algorithm
DB-R	Robotic Models Database
KiS	Kinematic Simulation Algorithm
DB-RT1	Robotic models kinematic performance
Promotion Filter	Model kinematic performance evaluation
DB-RT2	Promoted models kinematic performance
KiA	Kinetostatic Analysis
DB-RT3	Promoted models dynamic performance
C	Complexity Index
KP	Kinematic performance Index
FL	Flexibility Index
I	Overall Index

Fig. 1. The DOPA procedure schematic layout.

Step 1 – The compilation of the patient's *Clinical Identification Form* is the starting point of the procedure. It collects all the information necessary to classify the amputee's needs; different aspects are investigated in order to identify a patient's profile useful to portray a personalized level of life quality to be achieved after the prosthetic rehabilitation plan. An algorithm (*TaS*) based on the processing of this profile determines which upper limb activities are most significant for the given patient from the viewpoint of reaching a satisfactory functional autonomy in everyday living. The prosthesis will be designed aiming at performing these selected functional tasks. A further algorithm (*Char*) determines the values of the parameters involved in the selection of the optimal architecture by balancing the relative importance of the different factors which contribute to define the amputee's quality of life (e.g. expected level of functional autonomy, simplicity of the structure, easiness of control, etc.).

Step 2 – Kinematic simulations (*KiS*), performed for all the models in *DB-R*, generate the trajectories performed by the robot when attempting to fulfil the tasks assigned by *TaS*. The models with less than six DoF (hereinafter "Deficient Robots"), corresponding to simpler, less massive robot architectures (thus appreciated from the wearability viewpoint), execute the Reference Trajectories with a certain error which increases as the number of active joints decreases.

If the error overcomes the acceptable value fixed for every given task, then the robot model is considered not adequate to perform that activity. Only the robotic models which fulfil a given number of tasks, dependent on the functionality required by the subject (*Thresholds* $t_1,\ldots, t_4$), will move on to the next phases, whereas the others will be discarded. The structural simplification of the Deficient Robots and the corresponding worsening of their global functionality have to be evaluated with respect to the quality of life assigned (by means of the *Char* algorithm) to the given patient. A further kinetostatic analysis (*KiA*), performed for the "promoted" robots, provides the values of torque and power that all the actuated joints must generate to perform the successfully-executed tasks, defining the size of the actuators in a first approximation.

Step 3 – The artificial arm models are assessed in the last step of the procedure: their performance and the complexity of their architecture are evaluated by means of three purpose-built indices, all ranging from 0 to 1, named as *KP*, *FL* and *C* which, properly combined in an overall index *I*, univocally determine the optimal prosthesis architecture, i.e. the robotic arm with the simplest and lightest structure possible which can best satisfy the patient's personal requirements:

$$I = w_1 \cdot KP + w_2 \cdot FL - w_3 \cdot C \tag{1}$$

where $w_1, w_2, w_3 \in [0,1]$ are weighting factors which depend on the patient's profile.

The model with the maximum value for *I* designates the optimal architecture of the prosthesis associated with the given patient.

The main elements and algorithms of the DOPA procedure will be explained, in such a way to make their comprehension easy for the reader. In particular they will be outlined as if the procedure must guide the design of an ad-hoc prosthesis for a single patient; the intended implementation is actually different (see Section 3).

CLINICAL IDENTIFICATION FORM			
Label	***Definition***	***Value***	***Definition***
P1	Gender	P1.1	Female
		P1.2	Male
P2	Age	P2.1	0 – 15 years old
		P2.2	16 – 35
		P2.3	36 – 65
		P2.4	> 65
P3	Body-build	P3.1	Small
		P3.2	Medium
		P3.3	Large
P4	Non-dominant limb level of amputation *	P4.1	Distal upper arm amputation
		P4.2	Medial upper arm amputation
		P4.3	Proximal upper arm amputation
		P4.4	Shoulder disarticulation
		P4.5	Forequarter amputation
P5	Dominant limb level of amputation *	P5.1	Healthy (single extremity amputation)
		P5.2	Distal upper arm amputation
		…	…
		P5.6	Forequarter amputation
P6	Patient preferences about the prosthesis	P6.1	High predilection for comfort and appearance
		P6.2	Moderate predilection for comfort and appearance
		P6.3	No preference
		P6.4	Moderate predilection for device functionality
		P6.5	High predilection for device functionality
P7	Living situation	P7.1	He/she lives with someone else who can aid him/her
		P7.2	He/she lives alone, but someone is often present
		P7.3	He/she lives alone, someone is occasionally present
		P7.4	He/she lives alone in complete autonomy
P8	Work	P8.1	None
		P8.2	Houseman/housewife
		P8.3	Administrative employment
		P8.4	Technical employment
P9	Other activities (*All the activities not related to work*)	P9.1	None
		P9.2	Cooking (and kitchen-related activities)
		P9.3	Housework
		P9.4	Doing the shopping
		P9.5	Driving the car
		P9.6	Using home appliances (stereo, computer…)
		P9.7	Home maintenance and workshop activities
* "Non-dominant" (ND) is the injured upper limb of a monolateral amputee or the limb with the severest injury for a bilateral amputee; "dominant" (D) is the other limb. ND and D prostheses are the corresponding artificial arms that will replace the missing limb(s). An ND prosthesis should perform functions of support (simpler) to the D limb (natural or artificial).			

Table I. A schematic layout of the *Clinical Identification Form* with the *P-labels* meaning.

2.1 Clinical Identification Form: determination of the patient's main characteristics

Let us suppose we are going to rehabilitate an amputee with a custom-made prosthesis developed according to his/her personal requirements. The design process is thus subject-oriented and, for the sake of its significance and effectiveness, it should be objectively repeatable with a standard protocol for other amputees too; this means that proper information concerning the patient's expectations and impediments have to be systematically collected in a way suitable to automatic processing. This is possible by properly codifying the responses to the queries reported in the patient's *Clinical Identification Form* (Table I) by means of specific markers (called hereinafter *P-labels*). The form is actually a questionnaire and has to portray a well-defined patient profile upon which the architecture synthesis of his/her prosthesis will be based. Different aspects are investigated and, for all the fields, the patient is asked to tick off his/her choice among a number of pre-defined answers, in order not to fall into ambiguities.

The labels *P1–P3* refer to the patient's gender, age and body-build and are useful to determine potential upper limits on the prosthesis size; the kind of amputation (*P4*, *P5*) defines the subject's disease and thus his/her restrictions. The patient is also asked to point out his/her preference between functionality and wearability of the prosthesis (or a compromise), giving a direct indication useful to evaluate the robotic models (*P6*). In addition, with the purpose of defining the level of functional autonomy requested by the amputee, the field *P7* focuses on his/her living situation, since the same concept of functional autonomy depends on this aspect too: e.g. the personal needs of an amputee living alone are somewhat different from those of an amputee living with a person who can constantly give him/her aid. Finally, information related to work and other activities (*P8*, *P9*) draft the patient's expectations, making it possible to subsequently select activities more appropriate than others for the given subject. Labels *P9*, that can have more than one answer, guide the "patient-tasks" association performed by the *TaS* algorithm.

The fields in the form have been chosen trying to make them identify the main factors which condition the rehabilitation team's decisions when selecting an *existing* prosthesis for a given amputee, i.e. to translate the decision process into a technical systematic language. Based on the *Clinical Identification Form*, the procedure, which is intended to guide the design of *new* prostheses, can be repeated for many patient profiles according to the same protocol.

Once the *Clinical Identification Form* has been compiled, it is possible to represent the given patient's profile by means of an unequivocal alphanumeric code, suitable for processing by proper algorithms. A possible form of the codified patient's profile can be a "Structure" (i.e. arrays with "data containers" –called fields– which can house any kind of data), whose fields contain the patient's answers to the *Clinical Identification Form* (i.e. the values of the *P-labels*).

An example makes it easier to understand: let us suppose we are going to rehabilitate a monolateral shoulder disarticulated amputee, a male, 57 years old, medium body size, who expresses a moderate preference for prosthesis functionality with respect to its wearability, even if he prefers not to return to work after his injury. Let us assume that he lives alone, very close to some relatives, and that he would like his prosthesis to allow him to cook and to do the housework without others' help. His profile is therefore represented by the univocal structure shown in Table II.

Structures have been chosen to represent the patients' profile because it is possible to add, remove and/or modify fields (that can contain information of various kinds) without entailing radical modifications of the algorithms that manage them.

Structure	*Fields*	*Value*
Patient =	Gender:	*P1.2*
	Age:	*P2.3*
	Body-build:	*P3.2*
	Non-dominant limb amputation:	*P4.4*
	Dominant limb amputation:	*P5.1*
	Preference about prosthesis:	*P6.4*
	Living situation:	*P7.2*
	Profession:	*P8.1*
	Non-work-related activities:	*P9.2*, *P9.3*

Table II. Structures can represent the patients' profile.

2.2 DB-T database and TaS algorithm

Several activities were picked out from different literature sources (Anglyn & Wyss, 2000) and then completed and processed in order to characterize all the main upper limb functions by means of basic movements (motor tasks) as simple and general as possible. The activities were stored in the database *DB-T* along with associated markers (*T-labels*) which outline their main distinguishing characteristics (Table IIII).

In particular, the label *T1* provides the motor task identification code which is univocally linked to the task name, e.g. T1.1 = "Drinking from a glass". *T2* represents the activity macro-area, that is the general functional sector that the activity belongs to.

Since not all the activities have the same priority from the functional autonomy point of view, a prosthesis can be allowed to fail the performance of a certain number of tasks of minor importance and still be considered acceptable for a given subject. Based on their priority, the tasks have been ranked in five different groups corresponding to the *T3* values:

- T3.0: basic and minimal activities of primary importance that any prosthesis is compelled to perform satisfactorily. The ability to perform these tasks allows the patient to autonomously eat and go to the bathroom. The activities of this group are intended as performed by the subject also with the aid of supportive devices or special arrangements, and with large compensatory movements (the Reference Trajectories that model them, see below, respect these control strategies);
- T3.1: high relevance activities dealing with feeding and hygiene (limited to face and private parts). Use of supportive devices, special arrangements, and large compensatory movements is considered;
- T3.2: activities which allow the subject to autonomously take care of total body hygiene and dressing, and activities which make it possible to do without those special arrangements and devices potentially necessary to perform the motor tasks of the previous groups (e.g. the ability to "Cut food with a knife" makes it possible to do without special cutlery);
- T3.3: activities which allow the patient to carry out the most important operations concerning his/her work and non-work-related activities (for which special arrangements and devices are considered) and to live a normal social life (e.g. "Using the telephone"); activities relative to dressing which make it possible to do without special expedients (e.g. "Fastening buttons" allows the amputee not to wear shirts with special Velcro fasteners);
- T3.4: activities which make it possible to do without all the special expedients potentially required for the motor-tasks mentioned in the previous two groups.

The label *T4* establishes how many extremities are intrinsically involved in the activity. The label *T5* indicates the duty cycle of the motor task: the value for this label has been set considering reasonable temporal intervals for performing activities that an amputee can consider acceptable.
Finally, the label *T6* indicates the possible payload acting on the end effector to carry out the task, mainly[2] intended as the weight of an object held in the hand. Four weight levels have been set: none, light, medium, and heavy (0 N, 1 N, 5 N, 10 N).
DB-T also collects the end effector Reference Trajectories that model the performance of a motor task, normally requiring six DoF for positioning and orienting tasks. Every trajectory is provided by means of a certain number of nodes through which the terminal device must go with a given orientation; these nodes are fixed according to different criteria, mainly due to obstacle avoidance and humanlike movement replication. Different reasons (Section 2.5) have been suggested to represent the pose (position and attitude) of the terminal device by means of the spatial position of three points properly selected fixed to the end effector (Fig. 4a). Therefore, for every node of the trajectory, the terminal device pose is represented by nine coordinates, that provide the spatial positions of these points with respect to the fixed coordinate system; the nine coordinates are constrained by three equations expressing the constant relative distances (l_{12}, l_{23}, l_{13}) between the three points, and thus only six of them are independent:

T-label	**Definition**	**Value**	**Definition**
T1	Motor task name	T1.*i*; *i* = 1,2,…	
T2	Macro-area	T2.1	Feeding
		T2.2	Hygiene care
		T2.3	Dressing
		T2.4	Kitchen-related task
		T2.5	Housework
		T2.6	Doing the shopping
		T2.7	Driving the car
		T2.8	Using computers
		T2.9	Office/school tasks
		T2.10	Workshop task
T3	Priority	T3.0	First-priority task
		T3.1	High-priority task
		T3.2	Medium-priority task
		T3.3	Moderate-priority task
		T3.4	Auxiliary task
T4	Limb(s) involved	T4.1	Single extremity task
		T4.2	Bilateral task
T5	Duty Cycle [s]	Δt	Time to execute the task
T6	Payload [N]	T6.1	0 N
		T6.2	1 N
		T6.3	5 N
		T6.4	10 N

Table III. *T-labels* and their meaning.

[2] Some tasks require a different model of the payload: e.g. "Opening a drawer" foresees the exertion of a horizontal force. These special cases are treated separately.

Structure	*Fields*	*Examples*	
Task(i) =	Name (*T1*):	T1.1 (Drinking from a glass)	T1.47 (Fastening a zipper)
	Macro-area (*T2*):	T2.1	T2.3
	Priority (*T3*):	T3.1	T3.3
	Limbs involved (*T4*):	T4.1	T4.2
	Duty Cycle (*T5*), [s]:	6 (seconds)	5
	Payload (*T6*), [N]:	1 (Newton)	0
	Reference Trajectory:	$\mathbf{H}_{T1.1}^{ref}$	$\mathbf{H}_{T1.47}^{ref}$
	Position Tolerance in the destination node (*Tl1*):	*II*	*II*
	Position Tolerance in intermediate nodes (*Tl2*):	*III*	*II*
	Orientation Tolerance in the destination node (*Tl3*):	*I*	*II*
	Orientation Tolerance in intermediate nodes (*Tl4*):	*I*	*II*

Table IV. Examples of structures that compose the *DB-T* database.

$$(\mathbf{P_i} - \mathbf{P_j})^T \cdot (\mathbf{P_i} - \mathbf{P_j}) = l_{ij}^2; \qquad i, j = 1, 2, 3; i \neq j \tag{2}$$

For a sound human limb, performing these Reference Trajectories is not the only way to perform the tasks satisfactorily: for each motor task, a tolerance on the actual path of the end effector with respect to the Reference Trajectory was thus introduced in *DB-T* (see also Section 2.6). The tolerance values were established taking into account the intrinsic accuracy required by each task; four levels of tolerance were defined:

I. low tolerance (high accuracy is required)
II. medium tolerance
III. high tolerance (low accuracy is accepted)
IV. infinite tolerance (nought accuracy is accepted).

In conclusion, all the labels, the Reference Trajectory and the tolerable errors of a motor task are gathered in a structure (Table IV).

The information stored in *DB-T* is needed by several algorithms of the procedure. In particular, the Task Selection algorithm (*TaS*) associates a set of upper limb activities with the considered patient: the purpose is to customize the synthesis of the prosthesis architecture according to the functional needs of the amputee, orienting the design process to the opportunity to use the resulting prosthesis to perform a finite number of motor tasks considered as more important than others for the given patient. The tasks that are not regarded as significant will be ignored hereinafter in the application of the other algorithms for the examined patient.

The *TaS* compares the *P7–P10* labels characterizing the patient's functional needs with the *T2* label which identifies the task functional macro-area. Moreover, the comparison between the *P5* value and *T4* (Table V) makes it possible to determine whether the prosthesis to be designed for the given patient should follow the Reference Trajectories of the Non-Dominant (ND) and/or the Dominant (D) limbs (see note in Table I). For instance, for a

monolateral amputee (*P5* = P5.1) the prosthesis (ND) to be designed is not required to perform the task "Drinking from a glass" (for which *T4* = T4.1), because it is presumed that he/she can perform the activity with the sound limb.
On the other hand, in order to "cut food with a knife and fork " (*T4* = T4.2) the two prostheses for a bilateral patient (*P5* ≠ P5.1) should allow him/her to hold the food with a fork with the ND artificial arm and to cut it with the D arm.

	T4.1	T4.2
P5 = P5.1	-	ND
P5 ≠ P5.1	ND	ND and D

Table V: Determination of the Reference Trajectories to be associated with a given patient according to the comparison between *P5*- and *T4-labels*.

The output of *TaS* is the selection of N_{PT} motor tasks collected in *DB-T* that the prosthesis should be able to perform in order to satisfy the patient's functional needs. This selection will be referred to as *DB-PT* hereinafter. Fig. 2 outlines a schematic representation of the operation performed by the *TaS* algorithm. Let us define n_{ti} as the number of tasks with label *T3* = T3.*i* (*i* = 0, 1, …, 4), now gathered in corresponding groups G_{ti}, associated with the given patient; it holds that:

$$\sum_{i=0}^{4} n_{ti} = N_{PT} \tag{3}$$

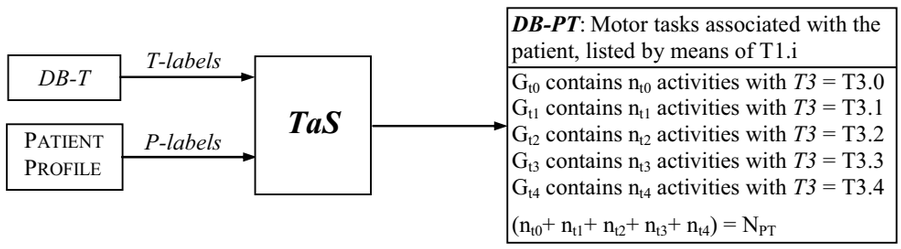


Fig. 2. Input and output of the Task Selection Algorithm.

2.3 Char algorithm: determination of "functionality vs. wearability parameters"

This algorithm processes the patient's profile and provides the value of some parameters involved in other algorithms of the procedure, thus determining another factor of personalization of the prosthesis synthesis process that characterizes the present method. In particular, two sets of parameters are determined: the *Thresholds*, involved in the *Promotion Filter* algorithm, and the *Weighting Factors*, used in the final evaluation of the prosthesis architectures.
Not all the activities selected for a given patient have the same importance from the functional viewpoint; for this reason the task label *T3* allows the motor tasks to be ranked in five groups according to their intrinsic priority; during the kinematic simulations, a prosthesis is allowed to fail the correct performance of a certain number of tasks (apart from those with *T3* = T3.0) and yet it can still be considered as acceptable. The limit on task failures is provided by the threshold $t_1,\ldots, t_4$ which are the ratios with respect to $n_{t1},\ldots, n_{t4}$ of

the tasks that a prosthesis must perform correctly[3]. For instance, if *Char* provides $t_1 = 0.85$, $t_2 = 0.7$, $t_3 = 0.6$ and $t_4 = 0.45$ for a given patient, a prosthesis model is still considered acceptable even if it fails to perform up to:

- $(0.15 \cdot n_{t1})$ tasks of group G_{t1} (those with labels T3.1)
- $(0.30 \cdot n_{t2})$ tasks of group G_{t2} (those with labels T3.2)
- $(0.40 \cdot n_{t3})$ tasks of group G_{t3} (those with labels T3.3)
- $(0.55 \cdot n_{t4})$ tasks of group G_{t4} (those with labels T3.4)

whereas no tasks with label T3.0 can be failed. The higher the priority of the task group (i.e. the lower the order of the *T3* label value), the greater the corresponding threshold with respect to the others. *Char* assigns the value to the thresholds $t_1,\ldots, t_4$ with a monotonic decreasing function by means of a proper process of the *P-labels*.
Similarly, *Char* determines the value of the factors w_1, w_2, w_3 that weight the relative importance of the investigated aspects in the final evaluation of the prosthesis architectures (kinematic performance, flexibility and complexity of the prosthetic devices; see Section 2.8). *Char* chooses the values in such a way that $w_1 + w_2 + w_3 = 1$.
The labels upon which *Char* assigns the parameter values are those representing the functional requirements of a given patient (P_7, P_8) and possible intrinsic upper limits for the complexity of the device (P_2, P_3), and, above all, the direct preference about functionality vs. wearability expressed by the amputee (P_6).

2.4 DB-R: robotic model database

This database collects the prosthesis architectures that will be simulated. The robotic models are serial kinematic chains with four links and a number of revolute joints differently arranged to form the three limb articulations (Fig. 3). In particular the links are the terminal device, the artificial forearm, the artificial upper arm, and the trunk which is considered as fixed to the global reference frame S_0. The *Y* and *Z* axes of S_0 belong to the patient's body sagittal plane, *Y* being vertical (pointing upward) and *Z* horizontal (pointing backward); the *X* axis is determined to form a right-handed triad. The origin of the frame is set at ground level at the intersection between the sagittal and the frontal plane. Each link is associated with an embedded reference frame whose origin is at the centre of its proximal joint (apart from the trunk frame that coincides with S_0) and whose axes are parallel to the S_0 axes when the upper limb is in its rest position (fully extended with the hand span turned inside): S_H, S_F, S_U are the frames fixed to the hand, forearm and upper arm respectively. The artificial segment dimensions, as well as those of the other body segments and other vector entities, were defined according to average anthropometrical proportions (Pheasant, 1996) and scaled to a unitary patient's height (i.e. considering H = 1 *m* in Fig. 3). The prosthetic models have from one up to six active joints (all actuated revolute joints) and up to two possible passive friction articulations at the middle of the forearm and upper arm segments respectively. Fictitious links with zero length are considered in the geometry of the articulations in order to connect the revolute joints (Figs. 3 and 4b).

[3] Threshold t_0 has not been introduced here, because $t_0 = 1$ for every amputee.

The passive joints, if they are present in a given model, replicate the spherical and/or revolute friction joints currently mounted in some prostheses for high level amputees, and they will not be part of the design, being already available[4]. Their possible presence was considered due to their essential contribution in performing some important activities, giving the artificial upper limb proper configurations before or after the activation of the powered joints. The passive spherical joints (Fig. 4b) were modelled as three consecutive revolute joints having concurrent and orthogonal axes (Fig. 4c). With this choice it is possible to represent the configurations of the passive joints by means of a (6×1) vector $\boldsymbol{\psi}$ which collects the elementary rotations:

$$\boldsymbol{\psi} = [\psi_{U1},\ \psi_{U2},\ \psi_{U3},\ \psi_{F1},\ \psi_{F2},\ \psi_{F3}]^{T} \tag{4}$$

where $\psi_{U(F)1} = \psi_{U(F)2} = 0$ if the upper arm (forearm) passive joint is revolute (Fig. 4d) and $\psi_{U(F)1} = \psi_{U(F)2} = \psi_{U(F)3} = 0$ if there is no passive joint at the upper arm (forearm). It is therefore possible to associate every robotic model in a generic configuration with a vector that gives information about the configuration of the passive joints.

Prosthetic active shoulders and wrists with up to three DoF are considered: the corresponding model of the spherical joints by means of three consecutive revolute joints is not unique. In fact, different arrangements of the three revolute joints form distinct actuated articulation models, different both from the kinematic and kinetostatic viewpoint.

All the possible combinations of the active and passive joints generate the prosthetic architectures of *DB-R*. A model containing d actuated joints (d = 1,…, 6) will be referred to as a d-DoF model; "Deficient Robots" will be generically called all the models with less than six DoF. The active joint motion variables of a model r are gathered in the vector $\boldsymbol{\theta}_r$. All the robot models were systematically named in such a way to univocally define their architecture, and are then stored in *DB-R* with their associated (4×4) homogeneous matrices $\mathbf{A}$ which express the orientation and the position of the reference system S_H embedded in the end effector with respect to the global frame S_0 – that is fixed to the thorax (Paul, 1981). Matricx $\mathbf{A}_r$, calculated by means of the Denavit-Hartenberg parameters (Denavit & Hartenberg, 1955), depends on the geometry of the artificial arm models (link lengths and arrangement of the joint axes, depending also on the configuration of the passive joints $\boldsymbol{\psi}_r$) and their motion variables $\boldsymbol{\theta}_r$.

The hand pose is represented by means of Natural Coordinates (De Jalon et al., 1986), i.e. the spatial position of three points, $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$, attached to the rigid body (Fig. 4a). In particular, $\mathbf{P_1}$ corresponds to the grasping point of the hand and was chosen as the point expressing the position of the terminal device; $\mathbf{P_2}$ is in the centre of the connection between the terminal device and the forearm; $\mathbf{P_3}$ was selected to form a rectangular triangle in a proper plane. The relative position of $\mathbf{P_2}$ and $\mathbf{P_3}$ with respect to $\mathbf{P_1}$ in the global frame univocally determines the orientation of the end effector. The coordinates in S_0 of the three points attached to the end effector of the generic robot model r can be determined with the following relation:

$$^{S_0}\boldsymbol{p}_i = \mathbf{A}_r(\boldsymbol{\psi}_r, \boldsymbol{\theta}_r) \cdot {}^{S_H}\boldsymbol{p}_i\,, \quad i = 1, 2, 3 \tag{5}$$

[4] The ball-and-socket joints can describe a cone with semi-angle of about 35° and weight 275 g. The revolute passive joints move in the range [0°-360°] and weigh a few dozen grams.

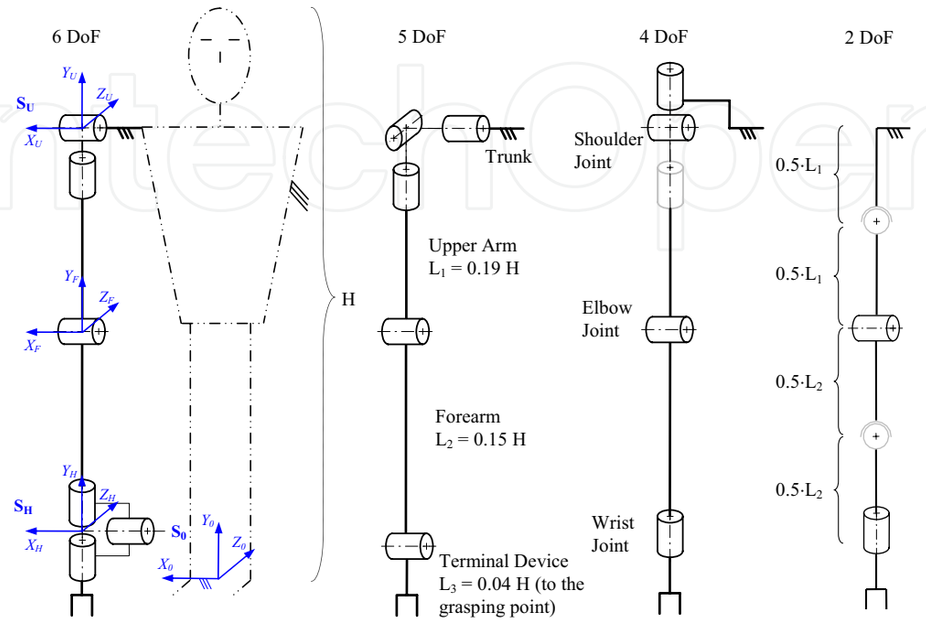


Fig. 3. Examples of prosthetic architectures; passive friction joints are drafted grey.

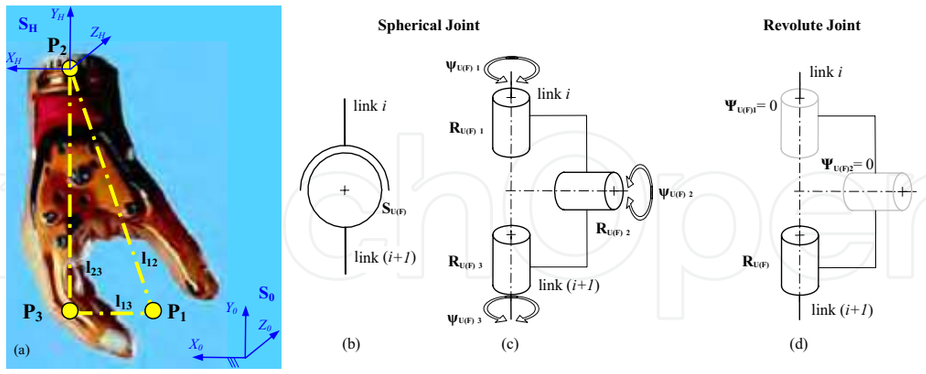


Fig. 4. (a) Three points are selected to represent the terminal device. (b) Passive spherical joint introduced at the middle of the Upper arm (S_U) and or the Forearm (S_F). (c) Alternative model of a spherical joint. (d) A passive revolute joint can be considered as a particular case of the spherical model of (c), with coplanar axes.

where ${}^{S0}\boldsymbol{p_i}$ and ${}^{SH}\boldsymbol{p_i}$ are (4×1) vectors that collect the homogeneous coordinates of $\mathbf{P_i}$ expressed respectively in S_0 and S_H (in S_H they are known and constant). The vectors $\boldsymbol{p_i}$ can be gathered in a (4×3) matrix $\mathbf{H}$ for a more compact hand pose representation:

$$ {}^{S_0}\mathbf{H} = {}^{S_0}\begin{pmatrix} p_{1x} & p_{2x} & p_{3x} \\ p_{1y} & p_{2y} & p_{3y} \\ p_{1z} & p_{2z} & p_{3z} \\ 1 & 1 & 1 \end{pmatrix} = \mathbf{A}_r(\boldsymbol{\psi}_r, \boldsymbol{\theta}_r) \cdot {}^{S_H}\begin{pmatrix} p_{1x} & p_{2x} & p_{3x} \\ p_{1y} & p_{2y} & p_{3y} \\ p_{1z} & p_{2z} & p_{3z} \\ 1 & 1 & 1 \end{pmatrix} = \mathbf{A}_r(\boldsymbol{\psi}_r, \boldsymbol{\theta}_r) \cdot {}^{S_H}\mathbf{H} \quad (6) $$

The Reference Trajectory of a generic task T1.i, that collects the desired hand pose at a discrete set of nodes, can thus be represented by a multidimensional (4×3×N_n) matrix ${}^{S_0}\mathbf{H}^{ref}_{T1.i}$ (where N_n is the number of the trajectory significant nodes). The generic term n_j gathers the desired homogeneous coordinates of the hand points $\mathbf{P_1}$, $\mathbf{P_2}$, $\mathbf{P_3}$ when correctly passing through the node n_j of the trajectory T1.i [5].

$$ {}^{S_0}\mathbf{H}^{ref}_{T1.i}(n_j) = {}^{S_0}\begin{pmatrix} p^{ref}_{1x} & p^{ref}_{2x} & p^{ref}_{3x} \\ p^{ref}_{1y} & p^{ref}_{2y} & p^{ref}_{3y} \\ p^{ref}_{1z} & p^{ref}_{2z} & p^{ref}_{3z} \\ 1 & 1 & 1 \end{pmatrix}_{T1.i,n_j} \quad , \quad n_j = 1, \ldots, N_n $$

2.5 KiS: Kinematic Simulation algorithm

The *KiS* algorithm calculates the actual trajectory ${}^{S_0}\mathbf{H}^{act}_{T1.i}$ performed by the robotic models of *DB-R* when attempting to follow the Reference Trajectory ${}^{S_0}\mathbf{H}^{ref}_{T1.i}$, for each motor task T1.i (i = 1,…, N_{PT}) selected for the amputee and stored in *DB-PT*. The core of the *KiS* algorithm is formed by the inverse kinematic analysis which calculates the active joint variables $\boldsymbol{\theta}_r$ for the generic model r and for a desired pose of the terminal device in the trajectory node n_j of the task T1.i. In a few words, the algorithm solves the inverse position problem associated with the following system:

$$ {}^{S_0}\mathbf{H}^{act}_{T1.i}(n_j) = \mathbf{A}_r(\boldsymbol{\psi}_r, \boldsymbol{\theta}_r) \cdot {}^{S_H}\mathbf{H} = {}^{S_0}\mathbf{H}^{ref}_{T1.i}(n_j) \quad (7) $$

solved for $\boldsymbol{\theta}_r$ ($\boldsymbol{\theta}_r = \boldsymbol{\theta}_{r,T1.i,nj}$ is the solution). The vector $\boldsymbol{\psi}_r$ collects the kinematic variables of the possible passive joints and must be considered as a parametric entity to be set before carrying out the inverse kinematic analysis. The value of the scalars that it contains can be changed and the analysis can be solved again, thus providing a different solution in terms of $\boldsymbol{\theta}_r$. The simulation of a task T1.i requires to solve Eq. 7 for every node of the trajectory; each trajectory must be simulated by all the prosthetic models.

A generic task normally requires six DoF for positioning and orienting the end effector; therefore the 6-DoF models correctly perform the tasks. In particular, the equation

$$ {}^{S_0}\mathbf{H}^{act}_{T1.i} = {}^{S_0}\mathbf{H}^{ref}_{T1.i} \quad (8) $$

[5] Hereinafter the superscript S_0 will be omitted, unless necessary.

holds for all the T1.i associated with the patient.

In a general case the Deficient Robots are not able to perfectly follow the Reference Trajectory of a given task, due to the lack of the necessary DoF. In fact, the system of equations that represents the position kinematics of the manipulators (Eq. 7) generally has no solution for the models with less than six DoF. The difference between the actual end effector pose and the reference one must be minimized at every node n_j of the trajectory in such a way that the error committed on the actual pose of the terminal device can be considered acceptable for a satisfactory performance of the motor task, even if not perfect (see par. 2.6). The "Error Matrix" $\mathbf{E}_{T1.i}$ is defined as:

$$\mathbf{E}_{T1.i}(n_j) := \mathbf{A}_r(\boldsymbol{\psi}_r, \boldsymbol{\theta}_r) \cdot {}^{S_H}\mathbf{H} - {}^{S_0}\mathbf{H}^{ref}_{T1.i}(n_j) \tag{9}$$

The inverse kinematic analysis that provides an optimal solution for the indeterminate system of equations is based upon the Non-linear Least Squares Method, and solved by means of the Levenberg-Marquardt numerical algorithm (Dennis & Schnabel, 1996). In the analysis, the manipulator links are forbidden to interfere with external obstacles, in particular with the subject's body. Here, the trunk and the upper limb segments, that are modelled on the basis of average anthropometrical proportions, are schematically represented by clusters of spheres in order to be able to implement a known technique for the collision detection [6] required to tackle and solve the problem.

The scalar function f to be minimized in order to find an optimal solution is:

$$f = \sum_{k=1}^{3} [\alpha_k \cdot (\boldsymbol{p}_k^{act}(\boldsymbol{\theta}_r) - \boldsymbol{p}_k^{ref}(n_j))^{T} \cdot (\boldsymbol{p}_k^{act}(\boldsymbol{\theta}_r) - \boldsymbol{p}_k^{ref}(n_j))] + \Gamma \tag{10}$$

The parameters a_1, a_2, a_3, ranging from 0 to 1, are weights that make it possible to balance the minimization according to proper criteria. For instance, for tasks that do not require a specific orientation of the hand when passing through the nodes, $\alpha_2 = \alpha_3 = 0$. Γ is a scalar which depends on the collision response and gives f a large positive contribution when two body segments interfere. Therefore, the solution $\boldsymbol{\theta}_r = \boldsymbol{\theta}_{r,T1.i,nj}$ corresponds to the configuration of the manipulator that minimizes the squared distance of the actual position achieved by the three points of the hand with respect to the desired values, and that make the manipulator avoid obstacle interferences.

It is possible to change the value of the parameters $\boldsymbol{\psi}_r$ of the kinematic variables of the passive joints – within their range of motion, to repeat the inverse analysis and to find a new solution for $\boldsymbol{\theta}_r$. This iteration makes it possible to optimise the solution also in terms of the passive joints configuration: the optimal value for $\boldsymbol{\psi}_r$ is the one that provides the minimum value of the error at the destination point of the trajectory.

The choice to represent the position and the orientation of the end effector by means of the spatial position of three embedded points was made taking into account the cost function f of Eq. 10. Indeed, if the pose representation of S_H had been based on the spatial position of its origin and three angles (e.g. Euler angles), the function to be minimized in order to find an approximated solution for the Deficient Robots kinematics (and an exact solution for the 6-DoF models) would have included non-homogenous terms. The elements of the Jacobian matrix would have proved sensitive to scale-factors and adding distance and angles is not actually very sensible (Duffy, 1990). Moreover, the three angles representing the orientation depend on the succession of the elementary rotations that they correspond to, and this would

[6] The technique is based on Computer Graphics algorithms well known in the literature (Jimnez, 2001).

create problems in the definition of the orientation errors. Other techniques used in robotics to represent the orientation of a reference frame suffer from similar problems. The technique used in this study was inspired by the Natural Coordinates method (De Jalon et al., 1986).
The output of the *KiS* algorithm is a transient database *DB-RT1* that collects the kinematic performance of the robot models simulating the trajectories associated with the N_{PT} motor tasks selected for the patient. *DB-RT1* is structured in such a way to save all the actual trajectories performed by all the robotic models, expressed both in the "Cartesian space" and in the "Joint space".

2.6 Promotion Filter algorithm: evaluation of the kinematic performance of the robots

This algorithm establishes whether a prosthesis architecture satisfies the minimum level of functionality required by the amputee; among all the simulated robots, the models that do not prove adequate will be discarded at this stage, whereas only those remaining will be "promoted" to the subsequent steps of the procedure.
For each node n_j of the generic trajectory T1.i a "Tolerance Matrix" $\mathbf{T}_{\mathrm{T1.i}}(n_j)$ is assigned on the basis of the tolerance levels *Tl1*, …, *Tl4* associated with the task T1.i (Section 2.2):

$$\mathbf{T}_{T1.i}(n_j) = [t_{lm}(n_j)]_{\mathrm{T1.i}} ; \quad t_{lm}(n_j) := ((p_{lm}^{act}(n_j) - p_{lm}^{ref}(n_j))^2)_{\max} \tag{11}$$

where l, m = 1, 2, 3 (m corresponds to x, y, z). The element l, m of $\mathbf{T}_{\mathrm{T1.i}}(n_j)$ represents the maximum squared difference between the actual and the reference values of the coordinate m of the hand point $\mathbf{P}_l$ considered still acceptable for a correct positioning and orienting of the terminal device at the node n_j of the task T1.i.
Let us consider the following step as performed for each single prosthetic architecture r (the subscript will be omitted); the algorithm compares the actual Cartesian trajectories with the Reference Trajectories of all the motor tasks associated with the patient, i.e. for each node n_j of the generic T1.i trajectory the actual Error Matrix $\mathbf{E}_{\mathrm{T1.i}}(n_j)$ is calculated:

$$\mathbf{E}_{\mathrm{T1.i}}(n_j) = [e_{lm}(n_j)]_{\mathrm{T1.i}} = [\,(p_{lm}^{act}(n_j) - p_{lm}^{ref}(n_j))\,]_{\mathrm{T1.i}}, \quad l, m = 1, 2, 3 \tag{12}$$

The matrix $\mathbf{T}_{T1.i}(n_j)$ collects the upper limits that the squared value of $\mathbf{E}_{T1.i}(n_j)$ elements can assume in order to consider the actual pose of the terminal device still acceptable with respect to the reference one. For every node n_j composing the trajectory T1.i the *Promotion Filter* algorithm checks whether the robotic model r is able to position and to orient its end effector with a sufficient accuracy, that is it must hold:

$$e_{lm}^2(n_j) \le t_{lm}(n_j), \quad \forall l, m = 1, 2, 3 \tag{13}$$

If the tolerance on the error is maintained for every node n_j of the Cartesian path, then the robotic model r is considered suitable to perform the task T1.i satisfactorily. This operation is repeated for all the tasks stored in *DB-PT* and for all the simulated models.
A "flag" $\boldsymbol{\delta}_{r,T1.i}$ describing the capability of the robot r to perform the task T1.i is set and saved: $\boldsymbol{\delta}_{r,T1.i}$ = 1 if the robot performance is satisfactory, $\boldsymbol{\delta}_{r,T1.i}$ = 0 in the opposite case. The tasks associated with the patient can be gathered in five groups G_{ti}, i = 0, 1,…, 4 (Fig. 2), so that it is possible to calculate how many tasks with label *T3* = T3.i (i = 0, 1,…, 4) are correctly performed. Let us define k = 1,…, n_{ti} as a pointer of a generic task of the group G_{ti}; the quantity:

$$\Delta_{ri} = \sum_{k=1}^{n_{ti}} \delta_{r,k}, \quad \mathrm{i} = 0, 1, 2, 3, 4 \tag{14}$$

represents the number of G_{ti} tasks that are correctly performed.

The architecture *r* can be promoted from the functional viewpoint if:

$$\Delta_{ri} \geq t_i \cdot n_{ti}, \quad \forall i = 0,1,2,3,4; \;\; t_0 = 1 \tag{15}$$

Finally, it is possible to build up another temporary database *DB-RT2* that collects information stored in *DB-RT1* relative to the promoted models only and that also reports the values of $\boldsymbol{\delta}_{r,T1.i}$ and Δ_{r0}, …, Δ_{r4} for each model *r*.

2.7 Kinetostatic analyses (KiA algorithm) and Workspace calculation

For a given promoted robot, velocity laws corresponding to each successfully performed task are calculated: this is possible by interpolating the values of the active joint variables at the path nodes and taking into account the duty cycle that has been presumed for each task. It is then possible to perform kinetostatic analyses of the robot, considering the mass of the robot links and joints (hypothetical values) and the force acting on the terminal device potentially required by the tasks. The analyses are carried out by means of the Newton-Euler recursive algorithm for all the promoted robots and their corresponding correctly performed tasks The dynamic performances of the prosthetic architectures, in terms of torques and powers of their active joints when accomplishing the tasks, are summarized in a new database, *DB-RT3*, structured like *DB-RT1* and *DB-RT2*. Based on these outcomes, it is possible to evaluate a rule of thumb approximation of the size of the gearmotors that drive the articulations: for this purpose, for each robot model *r* and for each of its active joints *l*, the maximum power required of the actuator, $W_r(l)$, is calculated and stored in *DB-RT3*.
The reachable workspace volume (WS_r) of each promoted robot *r* is also calculated. The numerical algorithm used for this purpose, based on a very common technique known in the literature (Huang et al., 1996), considers the geometry of the manipulator, the arrangement of the joints and their range of motion as well as the presence of the subject's body, considered for the interference avoidance in the calculation. The joint ranges of motion of a promoted prosthetic architecture are calculated taking into account only the correctly performed tasks, whereas the joint excursions corresponding to a failed task are ignored.

2.8 Definition of the indices for the global evaluation of the arm architectures

This is the last step of the procedure, where the artificial arm models are evaluated: their functionality and the complexity of their architecture are assessed by means of proper indices which are not intended for applications outside this context. Their purpose is to provide a comparison between manipulators that operate under the same boundary conditions (determined by the patient, the input of the whole procedure) in order to identify the model that provides the optimal compromise between functionality on one hand and wearability, whose concept is defined specifically in this study, on the other.
The three indices presented here range from 0 to 1, in order to normalize the minimum and the maximum "values" (even if theoretical) of the features that they must portray.

KP: Kinematic Performance Indicator

The promoted robotic models guarantee at least the lowest level of functionality, fixed by means of t_0,…, t_4 thresholds and checked at the *Promotion Filter* (Eq. 15). It is now necessary to determine how well a robot satisfies the given functional specifications, in order to distinguish which prosthetic architectures are better than others. For this purpose a *Kinematic Performance Indicator* KP_r is defined for each model *r*. By referring to the definition of n_{ti} (Section 2.2) and Δ_{ri} (Eq. 14), the quantity

$$\sum_{i=1}^{4} \frac{\Delta_{ri}}{n_{ti}} \tag{16}$$

globally measures how well the model overcomes the minimal level of functionality (associated with the distinct G_{ti} groups) evaluated by the *Promotion Filter* algorithm. The thresholds $t_1,\ldots, t_4$ were set with the aim of differentiating tasks having different levels of importance. It is reasonable to extend this concept here, by weighting the terms of the previous sum with the same parameters $t_1,\ldots, t_4$, in order to assign a higher relevance to the accomplishment of important tasks in this evaluation too. KP_r is thus defined as:

$$KP_r = \frac{\sum_{i=1}^{4} \frac{\Delta_{ri}}{n_{ti}} \cdot t_i}{\sum_{i=1}^{4} t_i} \tag{17}$$

Since all the promoted robots can successfully perform the tasks with label *T3* = T3.0, the term $(\Delta_{r0} \cdot t_0 / n_{t0}) = 1$ was not introduced, being meaningless in this evaluation step.

FL: Functional Flexibility Index

In order to provide an index related to the flexibility of the manipulator model with respect to the accomplishment of whatever activities, the reachable workspace volume was considered as a measure of the capability to perform a generic task. The *Functional Flexibility Index* FL_r is defined for each model r as:

$$FL_r = \frac{WS_r}{\max_r (WS_r)} \tag{18}$$

The denominator, corresponding to the promoted robot with the widest workspace, was introduced in order to set the maximum value of FL_r at 1.

C: Complexity Index

Functionality is not the only specification required of a good prosthetic device: the system complexity, the weight and the cost also play an important role in a prosthesis design. For this purpose, the number of the actuated joints and the size of the gearmotors driving them is assumed in a first approximation as a global estimation of these aspects. For each promoted d_r-DoF model r, the maximum values of power that its active joints must be able to provide in order to perform all the satisfactorily completed tasks were calculated (and collected in *DB-RT3*, Section 2.7). In this study, the power required of an actuator $W_r(l)$ is defined as a rule of thumb measure of the complexity of the joint l that it drives. Let us define the scalar

$$TW_r = \frac{\sum_{l=1}^{d_r} W_r(l)}{\eta^{d_r}} \tag{19}$$

which represents the sum of the maximum powers of the active joints; $\eta \in [0,1]$ is a sort of "efficiency" that can be introduced to penalize to a greater extent models with many actuated joints (see Eqs. 20 and 21). It is possible to define the *Complexity Index* C_r as:

$$C_r = \frac{TW_r}{\max_r(TW_r)} \tag{20}$$

The index can vary from 0 to 1: the minimum value is only theoretical, because it is not likely that a prosthesis with only passive joints will pass the *Promotion Filter*. The maximum value is associated with the most complex architecture.

I: Overall Index

All the above defined indices can be combined to provide an overall index I_r whose value indicates the response of the promoted robot model r to the personal specifications of the patient, both in terms of functionality and wearability:

$$I_r = w_1 \cdot KP_r + w_2 \cdot FL_r - w_3 \cdot C_r \tag{21}$$

where w_1, w_2, $w_3 \in [0,1]$ are the weighting factors that depend on the patient's profile and are determined in the *Char* algorithm by means of the *P*-labels. I_r can assume negative values for those models that prove extremely complex with respect to their functional performance and/or with respect to the patient's requirements. The model with the maximum value for I_r designates the optimal architecture of the prosthesis associated with the given patient, i.e. the artificial arm which provides the best trade-off between the contrasting features required:

$$\max_r(I_r) \rightarrow \text{OPTIMAL PROSTHETIC MODEL} \tag{22}$$

3. Effective application of the DOPA procedure

The procedure has been presented as if it must be applied to a single amputee's profile, in order to personalize the synthesis of his/her optimal prosthesis architecture. As an immediate application, the results of this approach can guide practitioners in choosing the appropriate solution for a given high-level patient, on the basis of a systematic process. It may be the case that the architecture selected for him/her does not correspond to any device available on the market. The design of new components to be introduced in commercial prosthetic systems is thus required. The outlined method is useful for this aim too, defining which new active articulations must be designed (Fig. 5). In particular, the arrangement of the joints in the arm models determines the kind of motion which the new articulations must accomplish.

Morevoer, the results of the kinematic simulations (saved in *DB-RT1*) define the required range of motion of the joints. Finally, the KiA algorithm could be performed on a more detailed model of the chosen prosthetic architecture by referring to the actual patient's anthropometric data in order to determine the performance that the electromechanical actuators of the joints must provide (in terms of torques and powers), so as to correctly carry out the target functional tasks. The fundamental mechanical specifications are thus determined and the subsequent design activity can be started.

However, it is not feasible to design an ad-hoc prosthesis for each patient, as it would be too expensive a process. The DOPA procedure is thus intended to be applied to a huge number of patient profiles (theoretically, considering all the possible combinations of the *P-labels*) in order to define a limited selection of optimal or "sub-optimal" prosthesis architectures suitable to match different amputee requirements. "Sub-optimal" is intended as a degree of quality of the architectures associated with a single patient comparable with the optimal model (although

lower) characterized by a high value of the overall index *I* even if not the highest. Prosthesis models that prove sub-optimal for many amputees are more attractive from a global perspective than architectures being optimal for only a few patients. From a feasibility viewpoint, the choice of a good versatile architecture is actually more sensible than aiming to provide each subject with the best prosthetic device designed according to every single patient's personal needs.
The generation of a "patient population" by means of the permutation of all the possible values of the *P-labels* can be performed automatically (due to the "predefined-answer" nature of the *Clinical Identification Form*). In this perspective, it should not be surprising that an alternative arrangement of the algorithms and elements of the procedure was conceived in a slightly different way from what is presented above, being more appropriate for an automatic and iterative implementation (Troncossi, 2006).

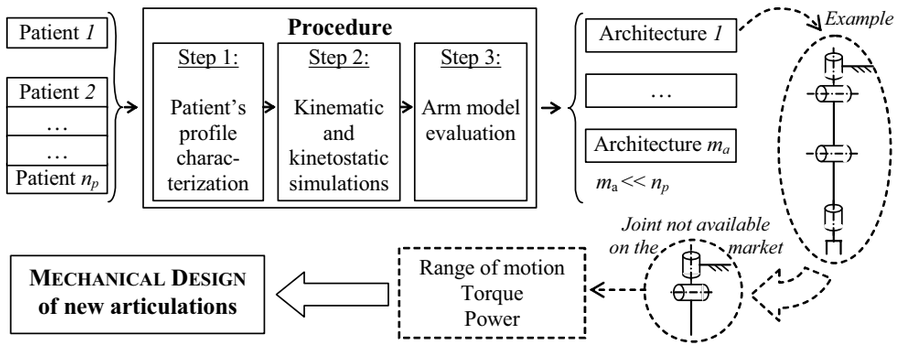


Fig. 5. Scheme of the intended application of the procedure.

4. Discussion and conclusion

The DOPA procedure presented in this chapter was developed in order to formalize principles for decision making in the choice and/or the design of upper limb prostheses for amputees with a high level disarticulation. The method makes it possible to tackle the problem of prosthetic rehabilitation from a general perspective, consistently taking into consideration both the clinical aspects and the technical issues involved in the design of upper limb prostheses. The DOPA algorithms make it possible to guide the synthesis of the artificial arm model that achieves the optimal compromise between a given patient's contrasting requirements in terms of functionality and wearability of the device. This is possible by means of a systematic investigation of the amputee's personal characteristics which generates a specific profile and by proper analyses and evaluations of many prosthetic solutions. The procedure is intended to be applied to a huge number of amputee profiles for a feasible application of its results. The generation of a "patient population" through the permutation of all the possible values of the *P-labels* can be performed automatically (due to the "predefined-answer" nature of the *Clinical Identification Form*) and the presence of real amputees is not strictly necessary to make the procedure run. Hence, the method can be systematically applied without the need to have real patients available; the method was actually devised for this purpose too.

The critical aspect of the approach is that the evaluation of the prosthetic models is deeply affected by parameters (t_1,…, t_4, w_1, w_2, w_3) whose value strictly depends on the authors' choices when compiling the *Char* algorithm and that are discriminating for the significance of the final outcomes. A validation process to calibrate these parameters and to prove the real effectiveness of the method is thus required. This is actually the forthcoming step of the project, which entails clinical testing application of the tool and a comparison with the clinical experience for proper updating.

Moreover, it is the authors' opinion that a very good feature of the DOPA procedure is that it can be modified, simplified or expanded (for a more sophisticated use) with little effort, due to the "open" nature of both the algorithms and the internal database.

The effective use of the procedure is intended to provide a database which collects patients' profiles, their associated optimal prostheses and the performance of these with respect to certain functional tasks. This database will be useful to guide the design of new electromechanical articulations, by defining which joints are more important than others to satisfy the given requirements of many amputees (e.g. a humeral rotator rather than a flexion wrist, or vice versa, or both) and by providing technical specifications of the mechanisms to be designed (e.g. range of motion and power of the actuators).

A simplified version of the DOPA procedure was applied with the aim of providing the design guidelines of a novel actuated prosthetic shoulder. Details on this design process can be found in (Troncossi, 2006).

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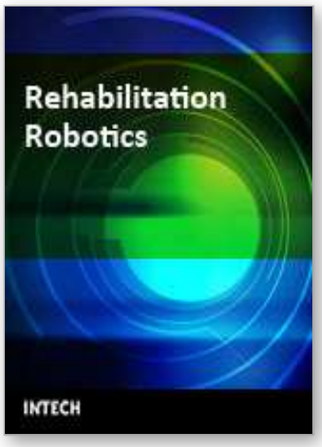

Rehabilitation Robotics

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The coupling of several areas of the medical field with recent advances in robotic systems has seen a paradigm shift in our approach to selected sectors of medical care, especially over the last decade. Rehabilitation medicine is one such area. The development of advanced robotic systems has ushered with it an exponential number of trials and experiments aimed at optimising restoration of quality of life to those who are physically debilitated. Despite these developments, there remains a paucity in the presentation of these advances in the form of a comprehensive tool. This book was written to present the most recent advances in rehabilitation robotics known to date from the perspective of some of the leading experts in the field and presents an interesting array of developments put into 33 comprehensive chapters. The chapters are presented in a way that the reader will get a seamless impression of the current concepts of optimal modes of both experimental and ap- plicable roles of robotic devices.

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