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Analysis of Elbow-Joints Misalignment in Upper-Limb Exoskeleton

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***Abstract*— This paper presents advantages of introducing elbow-joints misalignments in an exoskeleton for upper limb rehabilitation. Typical exoskeletons are characterized by axes of the device as much as possible aligned to the rotational axes of human articulations. This approach leads to advantages in terms of movements and torques decoupling, but can lead to limitations nearby the elbow singular configuration. A proper elbow axes misalignment between the exoskeleton and the human can improve the quality of collaborative rehabilitation therapies, in which a correct torque transmission from human articulations to mechanical joints of the device is required to react to torques generated by the patient.**

***Index Terms*— Exoskeleton; elbow singularity-free; human-robot axes misalignments; robot-assisted rehabilitation.**

I. INTRODUCTION

Exoskeleton robotized prostheses and devices for rehabilitation are typically designed to match and align their mechanical joints to human limb articulations, to achieve joint decoupling and a good coverage of the whole arm range of motion. The development of upper-limb exoskeletons needs to face important problems related to the complex shoulder movement. For this reason methodologies to design exoskeletons with improved ergonomic performances in terms of adaptability and human-robot joint self-alignment are presented in [1], [2], [3].

Moreover, singularities can play a significant role in defining the actual exploitable range of motion of mechanical chains. Exoskeleton singularities typically occur if rotational joint axes are aligned during their movement.

Some developed solutions have been optimized to face and limit singularities drawbacks at the shoulder, in order to exploit as much as possible the human shoulder range of motion [4]. On the other side, few emphasis has been given till now to the singularity affecting the upper limb and the exoskeleton at the elbow joint.

Modern medical rehabilitation robotic devices are characterized by force feedback in order to interact with the patient on the basis of the actual exchanged force and proper control techniques. Force is typically measured by torque sensors in correspondence with robot joints, or measuring motors overcurrents. In both cases the mechanical kinematics and joint disposition need to guarantee that force/torque generated at human arm joint space is correctly transmitted to the robot joint space: torques generated by human muscles have to be transmitted to robot joints. Human-robot joint alignment guarantees that torques generated by human muscles act selectively on correspondent mechanical joints, but kinematic singularities can influence actual transmitted torques to the mechanical device.

Experimental studies [5], [6] highlighted that some functional daily movements (*e.g.*reaching movements), are characterized by a complete extension of the elbow articulation. If a complete human-robot joint alignment is achieved at the elbow (typical condition of a number of pre-existing exoskeletons [7], [8], [9], [10]) a double singularity affects both the exoskeleton and the human-arm kinematic chain in the elbow extended configuration [11]. Problems and limitations can consequently arise during collaborative rehabilitation therapies, in which torques generated by patient (typically weak for impaired people) have to be transferred from human articulations to exoskeletal joints.

In this paper the misalignment between the exoskeleton and the human joints is investigated and the advantage from the controllability point of view of a proper elbow joint misalignment is shown. The kinematical structure refers to an innovative upper-limb exoskeleton currently being developed. The kinematic model of the human upper limb and of the exoskeleton being analyzed is reported in Section II. In Section III aspects related to elbow singnularities are identified and described, illustrating the advantages of introducing a proper joint misalignament, obtained by the peculiar mechanical structure of the conceived exeskeleton nearby the elbow. Finally, Section IV draws conclusions about already

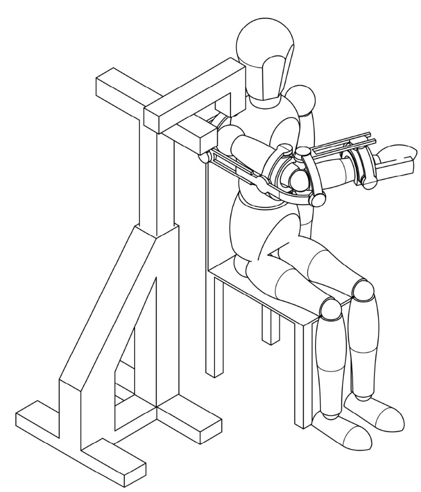


Fig. 1. Exoskeleton setup: a Cartesian holder for setting the gross position of shoulder joint; the human shoulder center stays floating w.r.t. the holding structure thanks to the peculiar exoskeleton kinematics.

TABLE I

UPPER EXTREMITY RANGE OF MOTION

Degree of freedom		Min	Max
Plane of elevation	$\{\phi_1, \mathbf{u}_{h,1}\}$	0	135
Angle of elevation	$\{\phi_2, \mathbf{u}_{h,2}\}$	-90	90
Internal rotation	$\{\phi_3, \mathbf{u}_{h,3}\}$	-55	70
Elbow flexion	$\{\phi_4, \mathbf{u}_{h,4}\}$	0	140
Angle of pronation	$\{\phi_5, \mathbf{u}_{h,5}\}$	5	160

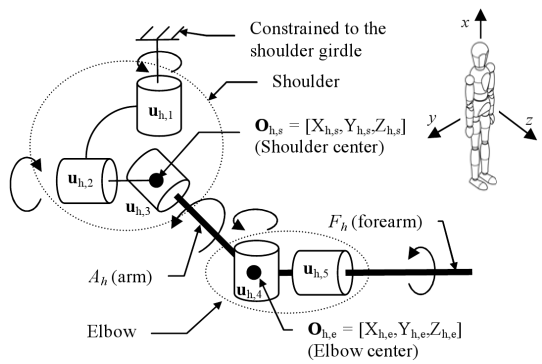


Fig. 2. Human arm kinematic model

completed design activities and further development steps.

II. KINEMATIC MODELS

Hereafter, kinematic chains and symbology of the human arm and of the exoskeleton are introduced. An alternative kinematic description and symbology to ISB description [12] is introduced to better highlight human arm and exoskeleton joint correspondence.

A. Human arm

Referring to Fig. 2 let us denote by:

1) *xy*, *yz* and *xz* the coronal, transverse and sagittal planes, respectively.
2) $\mathbf{O}_{h,s} = (X_{h,s}, Y_{h,s}, Z_{h,s})$ and $\mathbf{O}_{h,e} = (X_{h,e}, Y_{h,e}, Z_{h,e})$ the shoulder and elbow centers. $\mathbf{O}_{h,s}$ can translate freely with respect to the chest, due to the shoulder girdle movement.
3) $\mathbf{u}_{h,i}$ the rotational axis of the *i*-th joint of the human limb chain and ϕ_i denotes the value of its angle. Refer to Table I for joint names in medical nomenclature and their typical range of motion (see [13], [14], [15]).

Two singularity conditions may occur in the model:

- *shoulder singularity* ($\mathbf{u}_{h,1} // \mathbf{u}_{h,3}$) not representing an actual singularity in the human upper extremity shoulder, but exclusively due to the representation of shoulder joint by three serial rotation axes;
- *elbow singularity* ($\mathbf{u}_{h,3} // \mathbf{u}_{h,5}$) actually occurring when the upper arm and the forearm are aligned (human elbow completely extended).

B. Exoskeleton

The mechanism design has been optimized to cope with two distinct and relevant aspects of upper limb rehabilitation:

- adaptability and compensation of shoulder displacements to prevent undesired shoulder internal stresses due to joint axes misalignements (*shoulder adaptability*);
- optimization of the elbow usable workspace and dexterity, limiting singularities drawbacks (*topology optimization*).

Shoulder adaptability is achieved by a hybrid kinematic mechanism and a proper set of compliant links. (Fig. 3).

Topology optimization is achieved by a peculiar joint axes disposition at elbow level. Exoskeletons usually reproduce shoulder and elbow articulations by a spherical joint centered on the humeral head and a revolute joint aligned to the elbow rotational axis. The solution here presented, on the contrary, features two Cardan joints centered respectively on the humeral head and on the elbow center. Details on advantages of the presented solution are in Section III. For symbology related to the exoskeleton refer to Fig.3. Actual differences with [16] are related to the position of translational joints in the kinematic chain. A comparison of actual kinematic performances are outside the scope of this paper. For a deeper description of the kinematics and of kinematic equations refer to [11].

III. ELBOW TOPOLOGY AND SINGULARITIES

The kinetostatic relationship between two sets of degrees of freedom of two distinct spaces is defined by the Jacobian matrix $\mathbf{J}$.

The kinetostatic relation between the degrees of freedom of the upper-limb and the exoskeleton kinematic chains is:

$$\dot{\Phi} = \mathbf{J}\dot{\Theta}$$

denoting as:

- Φ the set of coordinates of the human arm
- Θ the set of coordinates of the exoskeleton

If a correct and exact alignment between correspondent degrees of freedom of the two kinematic chains is achieved (*i.e.* each exoskeleton joint is aligned to its correspondent joint of the human kinematic chain) the previous relation can be simplified as:

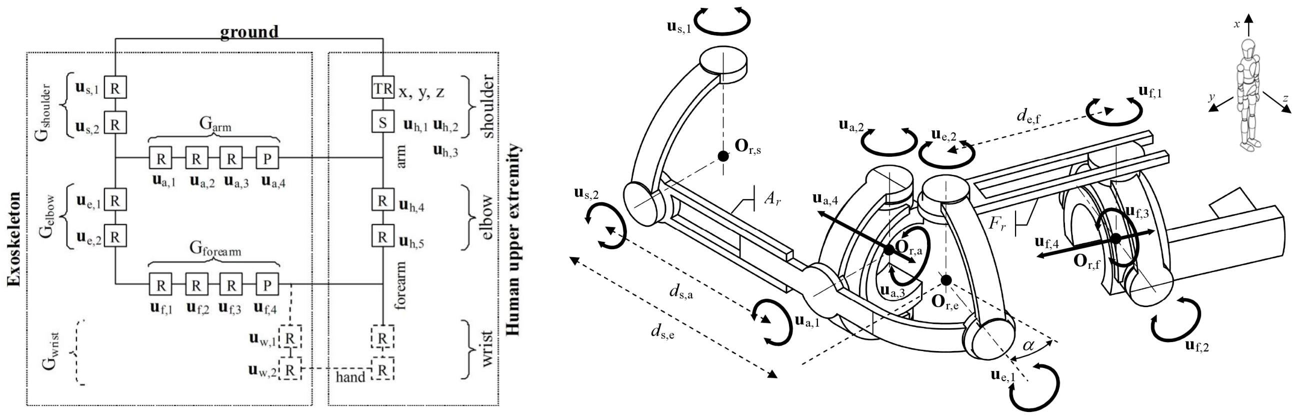
$$\dot{\phi}_i = \dot{\theta}_i$$

for each *i*-th degree of freedom, and the Jacobian matrix degenerates in the identity matrix:

$$\mathbf{J} = diag(1)$$

A. Elbow singularity

The elbow is intrinsically characterized by a singular configuration. Referring to Fig.2, if $\mathbf{u}_{h,3} // \mathbf{u}_{h,5}$ (complete elbow extension) the human arm kinematic chain is in singularity. If a joint-to-joint alignment is achieved between the limb and the exoskeleton, also the exoskeleton is consequently in singularity. The *double* singularity at the completely elbow extended configuration, which typically characterizes upper-limb exoskeletons due to human-exoskeleton elbow joints alignment, can lead to a not correct alignment between the



(a) (b)

Fig. 3. (a) Topological representation and (b) tridimensional view of the exoskeleton hybrid serial-parallel kinematic architecture.

elbow axes of the human $\mathbf{u}_{h,4}$ and of the exoskeleton $\mathbf{u}_{e,2}$. If $\phi_4 = 0$ (elbow completely extended) the human can perform intra-extra rotations of the shoulder $\mathbf{u}_{h,3}$ independently by the configuration of the exoskeleton [11], without inducing a proper orientation of $\mathbf{u}_{e,2}$.

Referring to (Fig.3), the misalignment between $\mathbf{u}_{h,3}$ and $\mathbf{u}_{e,1}$, identified by the α angle, influences the relationship between human and exoskeleton elbow joints kinematics. The kinetostatic relationship between the human and exoskeleton joints axes intersecting in the elbow ($O_{h,e}$) is:

$$\dot{\phi}_3 = \frac{\partial \phi_3(\theta_3, \theta_4)_{|\alpha}}{\partial \theta_3}\dot{\theta}_3 + \frac{\partial \phi_3(\theta_3, \theta_4)_{|\alpha}}{\partial \theta_4}\dot{\theta}_4,$$
$$\dot{\phi}_4 = \frac{\partial \phi_4(\theta_3, \theta_4)_{|\alpha}}{\partial \theta_3}\dot{\theta}_3 + \frac{\partial \phi_4(\theta_3, \theta_4)_{|\alpha}}{\partial \theta_4}\dot{\theta}_4;$$

B. Torques transmitted to exoskeleton joints

Due to the kinetostatic dualism exoskeleton and human arm joints torque are related by:

$$\mathbf{T_r} = -\mathbf{J}^T \mathbf{T_h}$$

denoting as $\mathbf{T_r}$ and $\mathbf{T_h}$ the torques of *r*obot and *h*uman joints respectively.

Similarly to velocities, a complete alignment between human and exoskeleton joints leads to the equation:

$$T_{r,i} = T_{h,i}$$

for each *i*-th joint.

Both in case of sensorized joints and in case of torque estimation by motor overcurrents measurement and in case of complete passive exoskeleton movements driven by the patient, a minimum torque transmitted to joints has to be guaranteed in order to make the resulting joints torque, due to human's generated torques by muscles, appreciable. This minimal level depends, in general, on the sensibility of the measuring system and mechanical frictions. Let us denote this minimum torque for the *i*-th exoskeleton joint by $Tmin_{r,i}$. If the torque transmitted to the *i*-th mechanical joint is lower than $Tmin_{r,i}$ the capability of the exoskeleton of reacting to human's generated torque is prevented. With these premises the kinetostatic analysis can lead to identify critical configurations of the elbow articulation in terms of movement fluidity and controllability, and to analyze the influence of the α angle on torques actually transmitted to the exoskeleton.

C. Influence of soft tissues and cuffs compliances

The mechanical constraints between the human arm and the exoskeletal arm are intrinsically compliant due to human soft tissues and softness of interfacing materials (*i.e.* cuffs).

Nearby singularities torques generated by cuffs on the human arm can be not sufficient to be transmitted to exoskeletal mechanical joints, resulting in a possible relative rotation between the human's and the exoskeleton arm, without a correct rotation/reconfiguration of the exoskeleton.

Cuffs can be, simply but exhaustively, modeled as linear and torsional springs, to take into account the effect of soft tissues reactions and mechanical compliances. Referring to Fig.4, C_a and C_f denote the cuffs constrained respectively to the arm and the forearm. Forces and torques exerted by cuffs are denoted respectively by $(F_{c,a}, T_{c,a})$ and $(F_{c,f}, T_{c,f})$ for the arm and the forearm:

$$F_{c,i} = kl_{c,i} * dl_{c,i}$$
$$T_{c,i} = kt_{c,i} * dt_{c,i}$$

where $kl_{c,i}$ and $kt_{c,i}$ denote the linear and torsional spring characteristics, $dl_{c,i}$ and $dt_{c,i}$ denote the linear and torsional displacements.

The total torque the cuffs can exert in constraining the human arm with respect to the exoskeleton structure is:

$$T_{s,a} = F_{c,a} * d_{ca} + T_{c,a} * \sin \delta_{ca} + T_{c,f} * \sin \delta_{cf}$$

and, denoting by $T_{h,i}$ the torque of the *i*-th human joint, the resulting torque along the arm axis $\mathbf{u}_{h,3}$ is:

$$T_{h,3} = T_{sa} \cos \delta_{ca}$$

Torque components along cuffs axes ($\mathbf{u}_{h,3}$, $\mathbf{u}_{h,5}$) are negligible, due to the extreme compliancy of the human soft

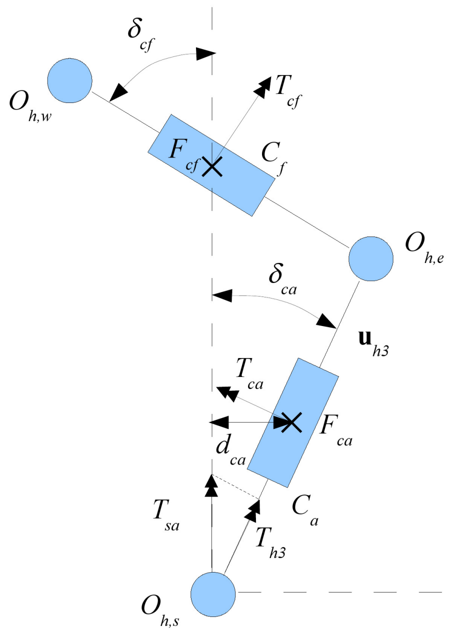


Fig. 4. Schematic representation of the cuffs reaction forces and torques on the two-link arm plane defined by shoulder, elbow and wrist center points.

tissues around the bones axes. Approaching the elbow singular configuration, d_{ca}, δ_{ca} and δ_{cf} decrease and the total torque the cuffs can exert on the human arm consequently decreases.

If a torque, exerted by the human, around $\mathbf{u}_{h,3}$ axis, generates torques in exoskeleton elbow joints below their minimum sensitivity levels ($Tmin_{r,3}$, $Tmin_{r,4}$), a relative rotation between the human and the device can occur, due to mechanical compliances, without a correct rearrangement of the exoskeleton configuration.

In conclusion, singularity drawbacks occur not strictly if $\mathbf{u}_{h,3} // \mathbf{u}_{h,5}$ but its workspace influence is function of constraints and tissues uncompliances. They can lead to a relative intra-extra rotation of the human arm with respect to the exoskeleton arm, causing a misalignment between $u_{e,2}$ and $u_{h,4}$ and incoherency between human and robot joints.

This aspect emphasizes the importance, previously mentioned, of introducing the α angle misalignment to univocally define the elbow exoskeleton configuration during extended movements and extend the actually exploitable limb range of motion in collaborative therapies. This drawback and limitation of some existing exoskeletons as been confirmed by interviews with physiotherapists.

D. Numerical results

Hereafter the torques transmitted to exoskeletal joints intersecting in the elbow ($\mathbf{u}_{e,1}$, $\mathbf{u}_{e,2}$) are analyzed. Both the influence of intra-extra rotations of the shoulder and flexo-extension movements of the elbow on transmitted torques, as function of the misalignment α, are investigated. Torque transmission ratios, and not absolute values, are plotted, to illustrate guidelines to follow, independently on actual exerted torques and sensibility levels. $\mathbf{u}_{r,3}$ and $\mathbf{u}_{r,4}$ will denote respectively $\mathbf{u}_{e,1}$ and $\mathbf{u}_{e,2}$ to better identify the correspondence between human and robot joints.

In Fig.5 the torque transmission ratio to $\mathbf{u}_{r,3}$ and $\mathbf{u}_{r,4}$ due to a torque applied around the axis $\mathbf{u}_{h,3}$ is plotted. It is worth underlining that the elbow misalignment α let the trasmitted torque $T_{r,3}$ to be amplified, facilitating the exoskeleton elbow rearrangement, reducing the risk of incurring in joint mechanical blocks due to friction effects, during shoulder rotational movements nearby the singularity.

In Fig.6 the torque transmission ratio to $\mathbf{u}_{r,3}$ and $\mathbf{u}_{r,4}$ due to a torque applied around the axis $\mathbf{u}_{h,4}$ is plotted. These graphs are useful to analyze what would happen if a correct rearrangement of elbow joints does not occur; it can be due to an undesired rotational movement of $\mathbf{u}_{h,3}$ (with respect to $\mathbf{u}_{r,3}$) due to soft tissues and cuffs mechanical compliances nearby the elbow extended configuration. Increasing the α value will allow to avoid mechanical blocks with a proper torque trasmission from human elbow to exoskeleton elbow joints.

Limitations in increasing α are due to the necessity of keeping $\mathbf{u}_{r,3}$ axis outside the range of motion of the forearm ($\alpha < 40°$), not to incur in singularities during elbow flexional movements (ref. Table I). For this reason the quantitative analysis has been performed for $0° < \alpha < 30°$.

IV. CONCLUSIONS

Most of currently available exoskeletons for upper limb neuro-rehabilitation are affected by shoulder uncompliancy and lack of adaptability in terms of movements critical conditions (*i.e.* singular configurations). For these reasons an innovative mechanism as been conceived in order to face these two widespread problems. In this work a particular focus has been put on relevant torques transmission aspects from the human articulations to the exoskeletal axes, leading to improvements in robot controllability by the human and torque transmission nearby the elbow singularity. Modern exoskeletons require to collaborate with the patient in achieving the final goal of the therapy and, consequently, a significant transfer of torques from the human articulations to the mechanical joints of the exoskeleton is required. Low level of torques transmitted to mechanical joints can lead to mechanical problems in following the patient's action, due to mechanical frictions and joints minimum sensitivities. In this study, the influence of joints misalignment nearby the elbow is investigated, highlighting the advantages in terms of torque transmission ratio to the exoskeletal joints nearby the elbow singularity. Nearby the elbow extended position the human arm can rotate freely with respect to the exoskeleton around the arm axis, due to mechanical compliances typical of human tissues and cuffs employed to constrain the arm to the exoskeleton. Compliances lead to have the elbow axis of the human misaligned with respect to the elbow axis of the robot. This undesired and unavoidable rotation can be correctly faced by a proper singularity-free mechanical elbow in the range of motion of the human arm. This study will be employed for the correct dimensioning of an innovative

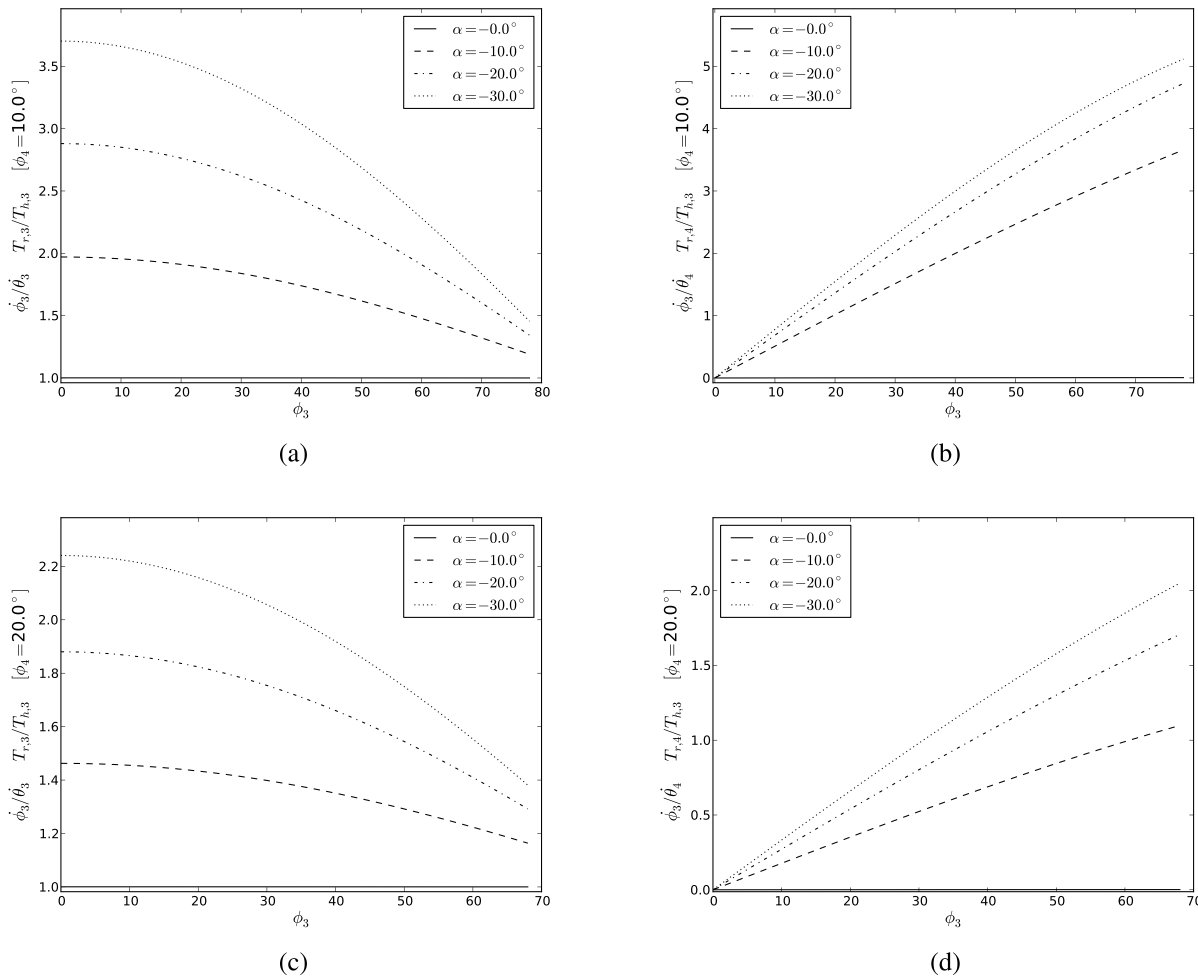


Fig. 5. Torque transmission ratios of T_{h3} at different flexion angles: (a-b) $\phi_4 = 10°$; (c-d) $\phi_4 = 20°$

exoskeleton currently being developed. The theoretical dimensioning phase will be followed by experimental results to assess the improved quality of motion transmission for human-driven complex movements with the elbow almost extended.

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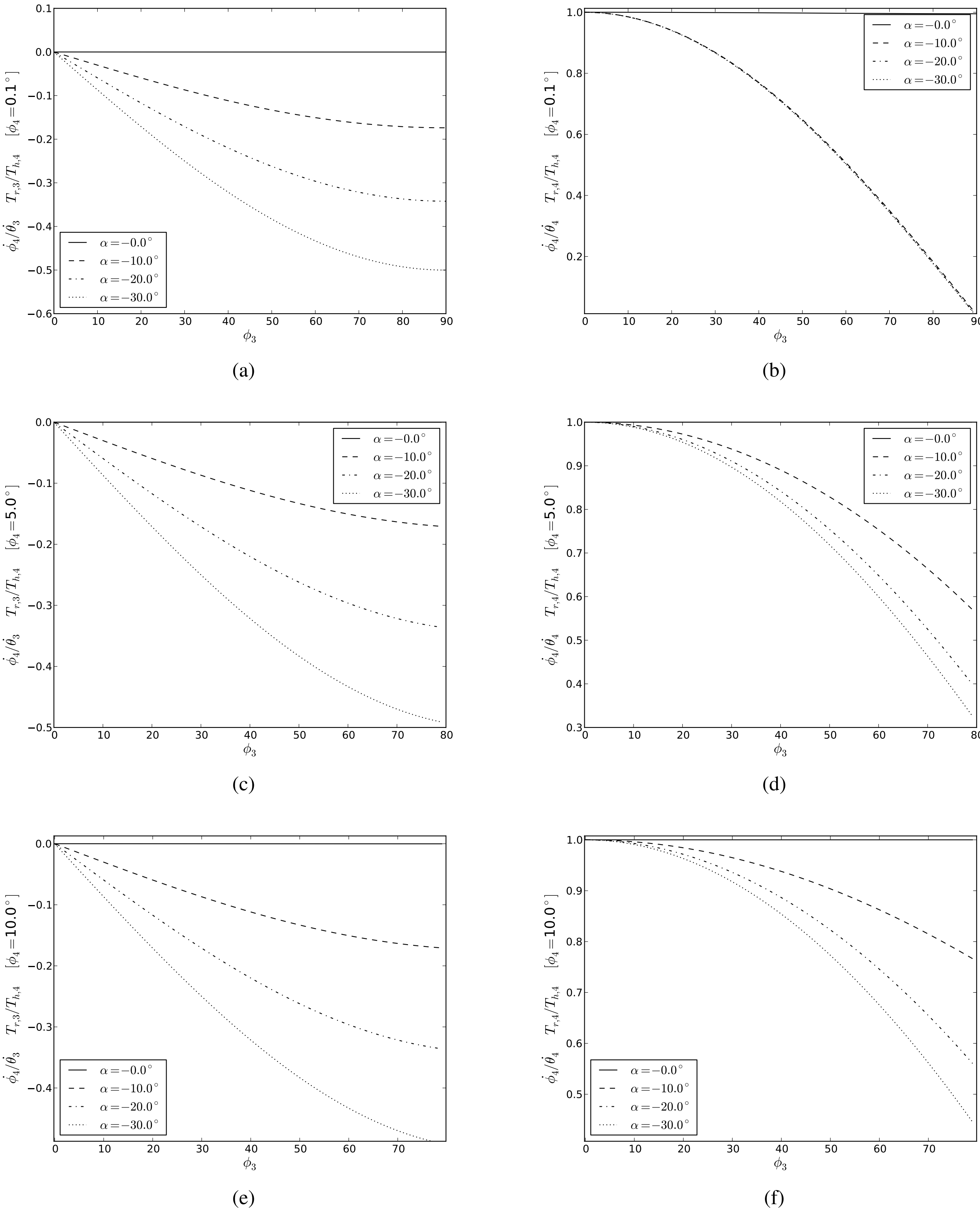

Fig. 6. Torque transmission ratios of T_{h4} at different flexion angles: (a-b) ϕ_4 = 0.1°; (c-d) ϕ_4 = 10°; (e-f) ϕ_4 = 20°