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HEXOTRAC: A highly Under-Actuated Hand Exoskeleton for Finger Tracking and Force Feedback.

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Abstract—**Exoskeletons offer an intuitive method for actuating multiple DOF of the body; this makes them attractive for applications where generation and coupling of artificial forces to the limbs is needed. Force feedback hand exoskeletons have been continuously considered for whole hand haptic interaction in virtual reality simulators, in teleoperation setups and for rehabilitation. In hand exoskeletons finger tracking, actuation and transmission systems must be embedded in confined spaces, matching at the same time the profound dexterity of the hand transparently and without causing a burden. Most of the design approaches for such systems have remained largely experimental due to hardware limitations, impacting heavily on important functional and ergonomic factors. This paper presents the design of a novel 3-digit hand exoskeleton, which addresses the issues of finger tracking and force feedback. It proposes a new approach for the application of the feedback force with a single attachment at the fingertip through a 6DoF kinematic chain. This kinematic linkage allows for unconstrained reach of the fingers within their full workspace and facilitates a sensor system for high resolution 6DOF tracking of the fingertips. At the same time the highly under-actuated mechanism permits application of a bidirectional feedback force at the fingertips. The hand exoskeleton fits an large range of hand sizes and requires no mechanical alignment between the linkage and the fingers, whatsoever. Preliminary results show the efficacy of this system as a tracking and force feedback device for the hand.**

I. INTRODUCTION

Kinaesthetic feedback devices can be traced several decades back when mechanically coupled master-slave systems were initially deployed in teleoperation settings for the performance of hazardous tasks. Since then, several haptic devices have emerged, which ranged from task specific force feedback desktop devices, lower body and upper body exoskeletons for teleoperation, VR and rehabilitation [1, 2].

Exoskeletons form a good solution to the problem of satisfying the body's workspace by matching its articulations through an exoskeletal structure. In teleoperation and VR, where interaction forces are generated through anthropomorphic robots or avatars, exoskeletons form a straightforward method for mapping these simulated forces to the user's body [3, 4]. As a result many exoskeleton systems and configurations have emerged from upper limb, lower limb [5] and full body exoskeletons [6, 7]. Whole hand haptic devices in the form of hand exoskeletons have demonstrated the potential to conform to the requirements of isomorphism, portability, range of motion and workspace, identified by [8] as necessary prerequisites for force feedback hardware attached to the hand. However, despite the continuous efforts to apply them as force feedback devices for teleoperation, tele-robotics and virtual reality, which date back to the early 90's, they have not managed yet to succeed as generic force feedback tools. The limited success of force feedback hand exoskeletons is probably not due to a flaw in the overall concept but lies with limitations imposed by the current actuation technologies, the available materials, and more importantly with the adopted designs for the transmission of forces to the fingers. The stringent ergonomic requirements, the dexterity of the hand and the acute sensitivity of touch have not yet been addressed to a satisfactory extent by any current device.

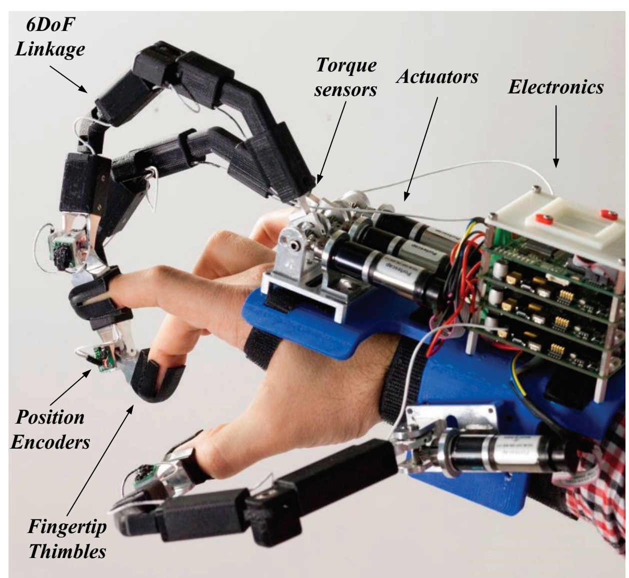

Figure 1 Prototype of the HEXOTRAC hand exoskeleton.

This work presents the design and development of an exoskeleton for hand tracking and force feedback, shown in Figure 1. The design of this exoskeleton focuses on the selection of suitable kinematics, which allow full reach of the digit's workspace, permit under-actuation and promote wearability. This is achieved through a novel non-

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anthropomorphic linkage composed of 5 passive and 1 active revolute joints, which manages to follow the digit's motions and allows 6DoF tracking of the fingertips by means of embedded sensors. Although this mechanism is highly under-actuated it can provide force feedback to both the extension and flexion of the fingers. The chosen configuration of revolute joints eliminates the need for any alignment between the mechanical linkage and the operator's fingers whatsoever, and suits a wide range of hand sizes.

This paper is organised as follows. Section II highlights important issues for the design of hand exoskeletons such as morphological aspects, tracking and actuation, toward a performant and ergonomic system. Section III provides some background on the biomechanics of the finger, which is important for the design of hand exoskeletons. Section IV presents the objectives of this design and provides a detailed description of the hardware including the kinematics, the tracking, and the actuation systems. In section V is presented a VR based setup, which has been developed and used for an initial evaluation of the system. Finally, section VI summarises the conclusions of this work.

II. Important Aspects of the Design of Hand Exoskeletons

There are several design aspects and system components that affect the performance, the transparency and the ergonomics of exoskeleton type tracking and force feedback devices for the hand. Some of the most important issues are discussed below.

A. *Method of Attachment to the Fingers*

Attachment of the exoskeleton to the fingers must be such that it does not obstruct the hand's motions and it ensures proper transmission of the feedback forces. Two attachment methods can be identified; the attachment at a single location on the finger such as the fingertip [9-12], and the multi-phalangeal attachment e.g. [1]. Single point attachment at the fingertips can be a solution which offers simplicity and increased haptic transparency in situations where fingertip contact is the main type of simulated interaction, such as in fine manipulation. This method of attaching the exoskeleton to the finger can reduce the generation of unwanted internal forces between the mechanical structures and the finger to a minimum. On the other hand, it is less effective in the simulation of interactions which require multi-phalangeal or palmar contact such as grasping. Exoskeletons with multiple attachments to the phalanges have been explored extensively because they offer a seemingly easier way of following the articulation of the finger and of directing feedback forces to the attached phalanges. However, they are more prone to causing encumbrance and unwanted internal forces due to the multiple attachments. Any exoskeletons must be secured sufficiently enough at its mounting locations on the hand and on the phalanges in order to follow the articulation of the fingers and to apply forces. At the same time it must not feel obtrusive. This is a challenge that is harder to achieve in systems with several phalangeal attachments. The finger's soft tissue not only prevents firm fixation of the exoskeleton but also becomes the recipient of unwanted forces and discomfort during exoskeleton operation. In addition any structure that is attached rigidly to the phalanges can interfere with the mobility of the adjacent joints by compressing and constraining the soft tissue around the joints.

B. *Exoskeleton Joint and Hand Joint Alignment*

An exoskeleton must articulate following the finger motions transparently. Depending on the kinematics of the exoskeleton's linkage it may be necessary to align the exoskeleton's DoF and the finger's joint axis e.g. [12]. Joint misalignment in rigid linkages which are designed to follow the finger kinematics can lead to constraints and internal forces during finger free motion and when feedback forces are applied [9, 13]. Proper alignment between the exoskeleton and the finger's joints instantaneous axes within the finger's workspace is not trivial to achieve. This is partially due to the complex kinematics of the finger and the nature of its joints, discussed in more detail in section IV.C. Proper alignment of exoskeletons with anthropomorphic/isomorphic construction is also impacted by the inherently compliant mounting of the exoskeleton onto the hand, which finally leads to inaccurate positioning of the exoskeleton joints with respect to the joints of the finger. This is further complicated in systems which are to be used by more than one user, since the anatomical differences between the user's hands call for fully adjustable mechanisms in order to facilitate joint alignment across users.

Therefore anthropomorphic exoskeletons that closely resemble the hand kinematics and which consist of multiple segments attached to the finger phalanges are generally more prone to misalignments and unwanted internal forces.

C. *Hand Tracking*

Hand tracking is a technology relevant to many fields of science and technology. It has applications in the medical field for hand assessment, rehabilitation, prosthetics, neuroscience, perception and psychology as well as in engineering; including master-slave teleoperation of robotic hands, VR haptics and other human computer interfaces. In force reflecting systems the position of the user's hand and fingers must be precisely known in order to control a slave robotic end-effector or for computing and rendering feedback forces from interactions taking place in a virtual environment. The quality of the tracking of the user's position is of fundamental importance in haptic feedback and in particular in kinaesthetic impedance feedback systems, where the force reference is usually a direct result of the tracked position of the user. For example in the case of teleoperation through impedance control the position of the user is used to drive the end effector of the robot. Upon interaction with the environment forces are generated between the robot and the environment, which are then measured and fed back to the user for rendering by the force feedback device. This necessitates reliable, high resolution and high update rate tracking of the user's position in order to ensure smooth force feedback reference forces and stable closed loop force rendering.

D. *Actuation*

The type of actuation and transmission systems employed and their mechanical configuration within the haptic device are defining factors for the performance, the morphology and in effect the applicability of a kinaesthetic feedback system [8]. The available technologies range from electric motors (with a large number of existing variants), hydraulic, pneumatic, magneto-rheological, electro-rheological, electroactive polymers, shape memory alloys, etc. Their operation can be toward the generation of active forces such as stiffness, or passive such as in systems implementing resistive action through brakes and dampers. Portable and wearable systems like hand exoskeletons are vastly limited in terms of suitable actuation due to weight and size restrictions, which prevent the use of sizeable actuators proximally to the body. In hand exoskeletons actuators can be mounted on the hand and coupled directly to the force application locations. There exist ample examples of hand exoskeletons of this type. In a different approach, actuators can be located remotely, away from the hand, in sites where they can be more easily supported [1, 14]. This type of actuation can reduce unwanted forces and fatigue due to the weight and inertia of the actuation system and it can provide higher levels of forces since larger actuators can be used. However, it may impact the hand's workspace and the fidelity/bandwidth of the force feedback due to the use of cable transmission systems, which like any tether can pose additional mechanical obstructions and which, in their typical implementation, are subject to friction.

III. THE BIOMECHANICS OF THE HAND

Several assumptions are commonly made when modelling the hand, which can lead to kinematic models that do not necessarily reflect the actual kinesiology of the hand and of the fingers. A review of the literature relevant to the biomechanics of the hand along with the common assumptions made can be found in [15].

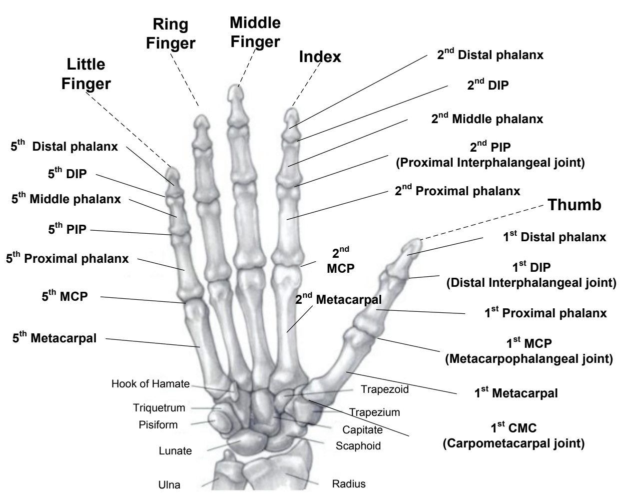

Figure 2 Palmar aspect of the right hand.

With reference to Figure 2 and Figure 3 let us examine some important aspects of the joints of the hand. The DIP and PIP joints of the four fingers are modified hinge joints, allowing rotation mainly around a single axis [16]. However, these joints are not exactly normal to the median plane of the fingers and they are not also parallel to each other. Furthermore, the articular surfaces of these joints create small rotations and translations to the instantaneous axes of rotation of the joint, within the joint's range of motion [15, 17, 18]. As a result the middle and distal phalanges of the fingers tend to supinate/pronate during flexion and extension [19] and under loading. This means that the Proximal-Middle-Distal phalanx chain connected with the DIP and PIP joints cannot be correctly modeled as a planar kinematic linkage. Nevertheless, this not so ideal planar kinematics model is adopted by most rigid link exoskeletons. The MCP joint is a condyloid joint (Figure 3 , b), which allows mainly rotational motion in the two axes of adduction/abduction and flexion/extension motions. In most exoskeletons who tackle adduction abduction motions this joint has been assumed to consist of intersecting orthogonal axes and has been modelled as a universal joint. However, the axes of the MCP joint are not intersecting, they are not orthogonal and their relative position changes within the range of the MCP joint [15]. The Carpometacarpal joints (CMC) of the four fingers do not provide any significant motion apart from compliance in the contouring action of the palmar area of the hand. Therefore in the design of hand exoskeletons they are usually not considered. This is not true though for the thumb. The human hand mainly owes its precision and dexterity to the CMC joint of the thumb. This is a saddle joint that allows rotation in two axes and a lateral motion in the joint leading to the thumb's radial abduction, palmar abduction and more importantly opposition. The kinematics of the CMC of the thumb are complex and cannot be simulated correctly by a set of fixed axis [20].

The most common finger model adopted in the design of hand exoskeletons is shown in Figure 4. In this model the finger has 4 revolute joints placed at fixed locations with respect to the finger links. The axes of the revolute joints R_1 and R_2 representing the MCP joint are intersecting and are orthogonal, effectively forming a universal joint. The axes of the revolute joints R_3 and R_4, which represent the PIP and DIP joints are parallel to the axis of R_2, and are normal to the phalanges of the finger. Therefore the revolute joints R_2, R_3 and R_4 create a planar mechanism. The finger model is finally completed with the rotation of the planar linkage around R_1. This is a simplified model which leads to the assumption that a properly aligned 4DoF anthropomorphic linkage can precisely follow the articulation of the finger. This section has shown that this assumption does not necessarily agree with the biomechanics of the finger, which cannot be described by fixed revolute joints. Furthermore precise positioning of an exoskeleton on a user's hand and its alignment with the finger's joints would be a tedious task and one with uncertain success.

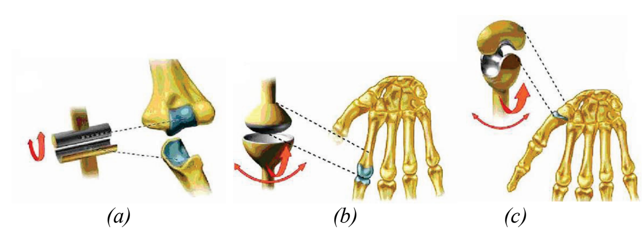

Figure 3 Graphical representations of finger joint types. (a) hinge joint (b) condyloid joint, (c) saddle joint. Adapted from [16]

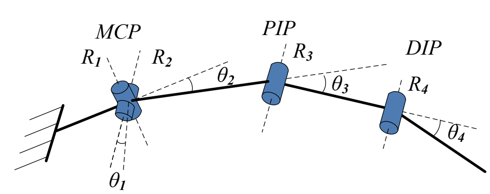

Figure 4 Common model of the finger kinematics.

IV. The Design of the Hand Exoskeleton

A. Design Objectives

The objectives for the development of this hand exoskeleton can be summarised as follows:

Wearability: The device must be easy to wear, and remove. The kinematic structure and the mountings should accommodate for different hand sizes without the need for significant adjustments.

Comfort: The device must be comfortable, without causing fatigue due to its mass and the way it attaches to the user's hand, even after long periods of use.

Workspace: The system kinematics should allow for effective haptic interactions within the functional workspace of the hand without constraints to the fingers.

Actuation: The system should be under-actuated with a single actuator per finger and with a force capable of constraining the flexion-extension motion of the fingers.

Force feedback: The available force levels should be adequate for generating the perception of the interactions.

Tracking: The delivery of force and tactile feedback to the fingertip is highly dependent upon precise tracking of the fingers. Therefore the proposed force feedback device should include an integrated tracking system with high resolution and high frame rate.

Weight: The actuation should allow for a lightweight, portable and compact system.

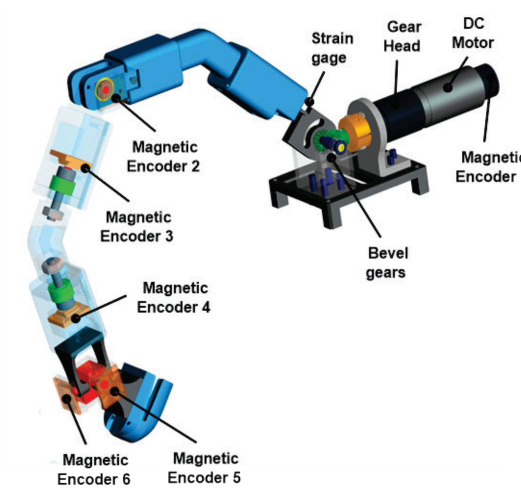

Figure 5 CAD view of the linkage of a finger showing the 1 st revolute joint actuated by the DC motor and the 5 passive and the joints with their position encoders.

B. Overview of the Device

Section III has shown how a hand exoskeleton with 4DoF is difficult to match the kinematics of the finger. This design proposes a 6DoF mechanism with a configuration which can follow the position and orientation of the fingertips in their entire workspace. To achieve the goals of wearability and ergonomic design actuation is based on a highly under-actuated mechanism with force feedback to the extension/flexion of the fingers. Feedback forces are transmitted to the distal phalanges of the operator's fingers by providing actuation only to the 1st out of the 6 revolute joints of the serial kinematic chain. Adopting the approach of one actuator per finger reduces the complexity of the system significantly in terms of hardware and control, and reduces the burden of the associated actuation and transmission components. The serial linkages are grounded on one side at the base and are attached to the distal phalanges of the fingers through thimbles. This single point of attachment of the links to the fingers allows for fast and easy mounting and removal of the exoskeleton and keeps the palm, the phalanges and the joints free of mechanical obstructions. The linkage kinematics provide 6 DOF (rotations and translations) to the fingertips and allow unobstructed motion of the fingers in their entire workspace. The kinematics of the system support a very large range of hand sizes without having to modify or adapt the linkage lengths. Furthermore the thimbles are easily interchangeable with a quick release pin mechanism for accommodating different fingertip sizes.

C. Kinematics

Figure 6 shows the joint arrangement for the index and thumb, while the middle finger is hidden for clarity. The serial kinematic chains for the fingers and the thumb have six revolute joints (q_{i0} to q_{i5}). The first joint for each exoskeleton finger linkage is actuated (i.e. q_{00} of the thumb, q_{10} of the index and q_{20} of the middle), while the rest are passive. Figure 7 presents the exoskeleton kinematics and the frames for all of the linkages. A representative example of the Denavit-Hartenberg kinematics parameters is shown for the index finger in TABLE I and TABLE II.

In order for the device to be able to provide meaningful force feedback, the kinematics should be able to convert the torque applied at the 1st joint into a force of sufficient magnitude and appropriate direction at the fingertip. Considering the high degree of under-actuation of the system with 5 passive and 1 active DoF, it is understandable that it is not possible to generate extremely accurate constraints. Figure 10 presents plots of flexion trajectories for the three digits. The plots are also showing the vector of the available feedback force created by a torque direction opposing the flexion of the fingers. On Figure 10, g and Figure 10 f is also shown the configuration of the fingers at several points along the trajectory. From these plots it can be seen that the direction of the force available at the fingertips is configuration dependent. However its vector is opposing the motion of the fingertip for a large part of the functional workspace and in any case it is always creating a torque to the MCP joint, which is opposing flexion.

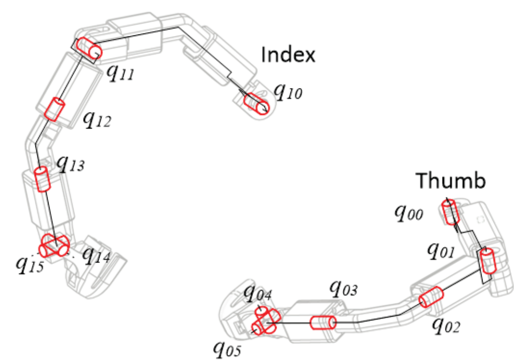

Figure 6 Joint arrangement of the index and thumb linkages (Middle finger not shown for clarity).

TABLE I INDEX FINGER DH PARAMETERS

i	$\alpha_{i-1}(m)$	$\alpha_{i-1}(m)$	θ_i *(rad)*	$d_i(m)$
10	$-\pi/2$	0	$q_{10}+\beta_{10}$	0
11	0	A_{10}	$q_{11}+\pi/2+\beta_{11}$	0
12	$\pi/2$	0	$q_{12}+\pi/2$	A_{11}
13	$\pi-\beta_{12}$	0	q_{13}	A_{12}
14	$-\pi/2$	0	$q_{14}-\pi/2$	0
15	$-\pi/2$	0	$q_{15}-\pi/2$	0

D. *Tracking*

All 6 joints of the exoskeleton linkage are equipped with magnetic position encoders as shown in Figure 5. The 1st joint is measured by the motor encoder with a resolution of 1024 CPR (counts per revolution), which after a gear ratio of 30.2:1 delivers a resolution of 0.2e-3 rad to the first rotary joint. The remaining 5 joints of the exoskeleton are equipped with Austria microsystems AS5045 12 bit rotary magnetic encoders delivering a resolution of 1.533e-3rad at these joints.

TABLE II INDEX FINGER DH NUMERICAL VALUES

Length	*(mm)*	*Angle*	*(deg)*
A10	*109.352*	β_{10}	16.85
A11	*59*	β_{11}	28.15
A12	*59.95*	β_{12}	*120*
A13	*27.5*	*0*	
A14	*13.57*	*0*	

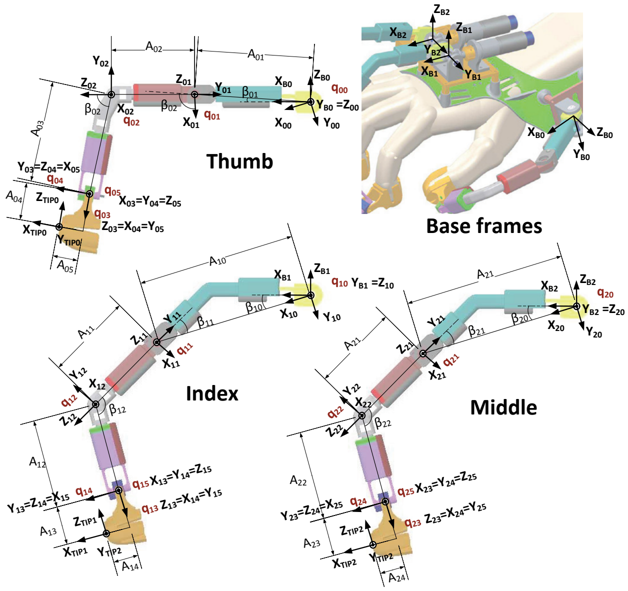

Figure 7 Kinematics of the hand exoskeleton.

Figure 8 shows the position and orientation tracking of the fingertips during a hand closure. The 6-DOFs Cartesian trajectory of the operator's fingertips X(t) can be computed using the forward kinematics of the exoskeleton according to $X(t) = fK(q(t))$. Where: $X(t) \in \mathbb{R}^{3m}$ are the 3 fingertip trajectories in Cartesian space stacked in a single vector, with *m*=6 the exoskeleton individual fingertip Cartesian space dimension; $q(t) \in \mathbb{R}^{3n}$ are the 3 finger joint trajectories stacked in a single vector, with *n*=6 the exoskeleton individual finger joint space dimension, and n_a =1 the exoskeleton individual finger actuated joint space dimension; $fK(q)$ is the exoskeleton forward kinematics function. This allows the measurement of the position and the orientation of the thimbles and therefore of the fingertips.

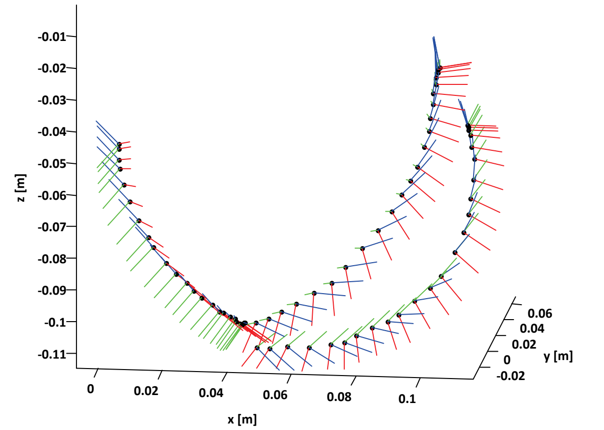

Figure 8 Position and orientation tracking during a hand closure trajectory.

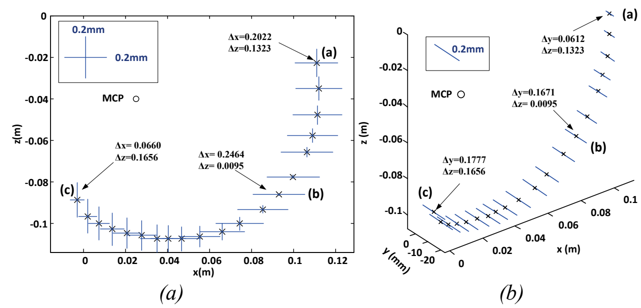

Figure 9 Typical fingertip tracking resolution in the finger's workspace. (a) resolution in x and z position measurement during a flexion trajectory. (b) resolution in y position measurement during a flexion trajectory.

TABLE III WORST CASE TRACKING ACCURACY

Axis	*Max position error(mm)*	*Max angle error(rad)*
X	*0.249*	*0.023*
Y	*0.190*	*0.031*
Z	*0.166*	*0.039*

The accuracy of the position tracking in Cartesian space is a function of the resolution of the encoders and varies within the workspace. The tracking accuracy can be analysed using the equation $dX = J(q,\dot{q}) \cdot dq$ with $dX \in \mathbb{R}^6$ the accuracy of the position and orientation description of the fingertip in Cartesian space resulting from the encoders' resolution $dq \in \mathbb{R}^6$ for a given posture described by the exoskeleton Jacobian matrix $J(q,\dot{q}) \in \mathbb{R}^{6\times6}$. The accuracy of the position tracking of the index finger during a natural flexion motion is shown in Figure 9. The markers indicate the 3D position of the fingertip tracked by the exoskeleton. This possible accuracy is indicated through bars (note: bars are scaled up to assist visualisation). Figure 9 (a) shows the position tracking accuracy along the X and Z while Figure 9 (b) shows the position accuracy along the Y. The position accuracy (xyz) on 3 points (a, b and c) along this trajectory is identified on the aforementioned plots. The accuracy of the fingertip's orientation tracking is computed in a similar manner. Finally, for the trajectory presented on Figure 9, the worst case accuracy corresponding for the 3 axis is presented in TABLE III.

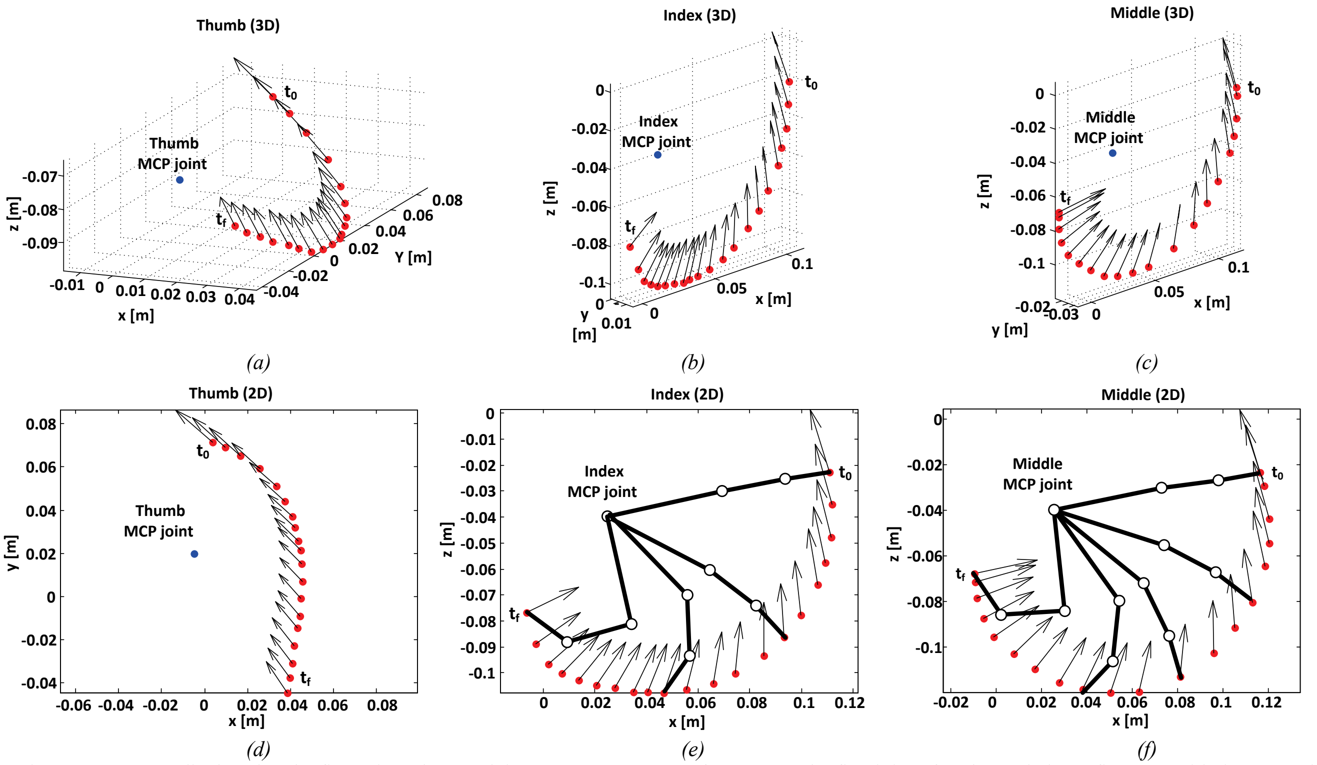

Figure 10   Force displayed at the fingertips when applying a constant torque of -0.2Nm at the first joint of each exoskeleton finger considering natural grasping motion trajectories

In order to examine the workspace of the exoskeleton against the approximate workspace of the finger, a simplified 4-joint model was developed similar to the one presented earlier in Figure 4. The total length of the model's finger was 9.5 cm. The plot in Figure 11 shows that the workspace of the exoskeleton measured at the thimble contains the index's fingertip workspace. It is also clear that the device can accommodate very different user hands' sizes.

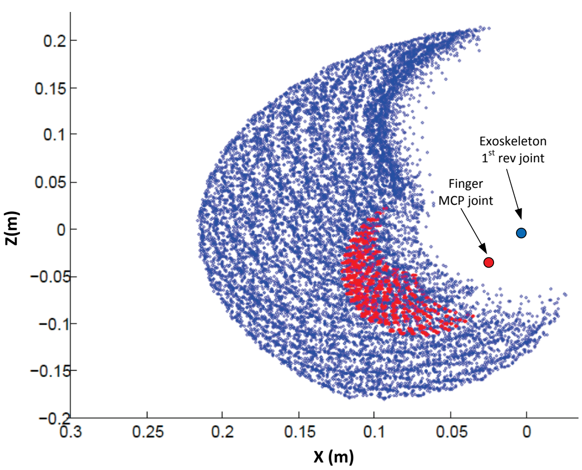

Figure 11   Plot of the workspace of the exoskeleton (blue) and of the finger (red) XZ

E   Actuation and Force Sensing and Control

Bidirectional actuation is provided by motors connected to the 1st revolute joint of each linkage. The actuators used in the 1st prototype are DC gear-motors from Portescap (model:16G88-220P) with a stall torque of 16mNm, continuous torque 5.5mNm, gear ratio of 30.2:1 and total mass of 37g per actuator. The axis of the motor output shaft is rotated by 90º and torque is transmitted to the 1st joint of the exoskeleton linkage through a pair of high precision anti-backlash bevel gears. This provides 0.48Nm at stall and 0.166Nm continuous available at the first exoskeleton joint. For a finger of 10cm in length (measured between the MCP joint and the fingertip) the available actuator torques would correspond to approximately 4.8N at stall and 1.66N continuous available to a fully extended finger parallel to the horizontal plane. Although these forces are lower compared to grasp and manipulation forces, they are adequate for creating simulations of haptic contacts. The exoskeleton incorporates torque sensors at the first link for measuring and controlling the interaction force at the fingertips. Each torque sensor is a cantilever beam whose deflection is measured by a pair of bilaterally bonded strain gauges in half bridge configuration. The torque sensor of every digit is measured by a dedicated 16bit resolution analogue to digital converter at a sampling rate of 1kHz. The applied force at the fingertip is calculated using the configuration of the exoskeleton and the measured torque at the 1st joint.

The individual finger interaction forces are controlled by dedicated microcontroller boards running 1kHz control loops and communicating over a LAN network with a host computer. In the current VR implementation, described in later in section V, the haptic simulation software reads the user hand and generates interaction forces to be rendered as force feedback by the hand exoskeleton. Using the exoskeleton joint angle readings and the system kinematics, the interaction forces are converted into reference torques at the motors and are transmitted over a UDP link to the exoskeleton microcontrollers. A block diagram of the system controller for one finger is presented in Figure 12. For every finger the reference torque is tracked by a PD controller, which uses the strain gauge signal as feedback of the applied joint torque. $\tau_{\text{int}\_des} \in \mathbb{R}^{3n_a}$ is the joint torque vector corresponding to the desired interaction force at the fingertip projected on the actuated joint space. Since the strain gauge signal contains both the interaction torque and the gravity torque a gravity torque block generates the torque signal for gravity compensation of the exoskeleton linkage based on the current configuration. $\tau_g \in \mathbb{R}^{3n_a}$ is the model-estimated gravity joint torque projected on the actuated joint space and $\tau_{str\_g} \in \mathbb{R}^{3n_a}$ is the strain gauges reading.

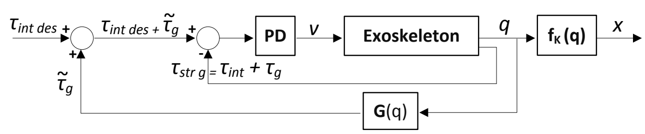

Figure 12 control block diagram

V. Preliminary Evaluation in a VR Scenario

In order to evaluate the exoskeleton as a tracking and force feedback device, a Virtual Reality Environment (VE) has been developed. The system uses a 27-inch stereoscopic display and an OptiTrack motion capture system with 4 cameras at 100Hz rate to track shutter glasses and the exoskeleton, providing immersion and interaction capabilities to the user. Optical motion capture data is combined with the exoskeleton fingertip tracking. This allows to fully track the pose of the user's fingertips, enabling the interaction with virtual objects. Small spheres replicate the fingertip movement inside the VE. An offset has been added between the exoskeleton and its virtual reference, so that the device can be used on the side of the screen, increasing the comfort of the user and preventing the exoskeleton from obstructing the display. A proxy-based method is used to compute the forces resulting from the interaction of the virtual fingertips with the objects populating the VE.

A. *Experimental Design*

An experimental study on stiffness perception has been designed and conducted using the VE setup. During the experiment, six subjects were asked to explore a VE populated by 4 virtual blocks, each with a different stiffness. The first task required subjects to identify the block with the highest stiffness. The second task asked subjects to identify among four blocks the block with the same stiffness as a reference block. The stiffness values k_i of the blocks were normalised to the maximum available torque so that $k_i \in [0, 1]$. The experiment required both tasks to be performed twice under condition A with stiffness levels k_{iA}=[0.1, 0.4, 0.7, 1], and twice under a slightly more difficult condition B with k_{iB}=[0.1, 0.3, 0.5, 0.7]. Virtual blocks under condition B presented smaller differences in stiffness between them, so they were hypothesized as more difficult to discriminate. The order of the virtual blocks was shuffled after each trial. Answers were given by subjects through virtual buttons shown in green, which also triggered force feedback. The size and positioning of the blocks allowed proper interaction, and the subjects could freely use any of the three tracked fingers.

B. *Results and Discussion*

On average, answers relative to task 1 are 79.2% correct, with an answer time of 24.15 seconds per trial. Results are better when considering only condition A, with a 92% of correct answers (66.7% for condition B). Interestingly, the average answer time for condition A was longer than condition B with 27.8 and 20.5 seconds respectively. Results are more homogeneous when observing data collected during the second task: correct answers average rate is 66.7% under both conditions, and average answer time is 37.2 and 35.8 seconds respectively under conditions A and B, with an average of 36.5 seconds. Observation of collected data suggests that condition B proved to be more difficult for subjects during task 1. Nonetheless, subjects answered faster under this condition, so there is a possibility that this affected their performance. Future investigation will also focus on user experience, in order to study if this behaviour depends on factors such as fatigue, boredom or a carryover effect: subjects faster answers may be due to the confidence acquired during the previous task, performed with the same setup. Results from task 2 suggest that the task itself proved to be tougher. This possibly levelled the differences between conditions A and B. Finally, the experimental study allowed evaluating the exoskeleton in a scenario exploiting its real time tracking and force feedback capabilities. Future experiments will evaluate the potential of the device in virtual multi-finger grasping and dexterous manipulation tasks.

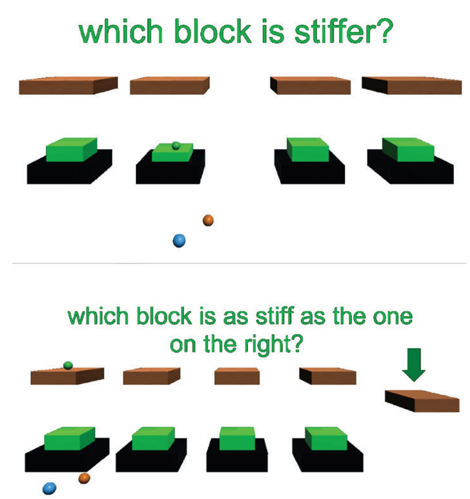

Figure 13 Screenshots of the two tasks composing the experimental study.

VI. Conclusion and Future Work

This paper presented the development of a highly under-actuated hand exoskeleton for tracking and force feedback. The proposed design implements a novel set of kinematics leading to a transparent mechanism. This kinematic solution not only satisfies the digit's workspace and accounts for all rotations of the fingertips but it is also suitable for a large range of hand sizes without the need for any mechanical alignment before use. At the same time the adopted kinematics allow for an extremely under-actuated device, which is capable of providing force feedback to the extension/flexion of the fingers. This under-actuated mechanism provides a configuration dependant force at the fingertips, which although is not a precise reconstruction of the simulated interaction forces, it can delivery rich perceptual cues. The device has been tested in a preliminary experiment through a VR generated haptic interaction where the subjects were able to discriminate different levels of stiffness.

The addition of tactile feedback at the fingertips such as the one presented in [21-23], will be also pursued in order to augment haptic feedback in VR and teleoperation. In addition work will continue toward the integration of the hand exoskeleton in the teleoperation of robotic hand slaves, addressing the kinematic, sensory and haptic feedback asymmetries, which are central to this highly under-actuated exoskeleton design when using it as a generic input and feedback device [24]. In terms of hardware future work will concentrate on the refinements of the design through the enhancements of the actuation and transmission system to provide higher forces. This will allow investigation of applications in areas such as hand rehabilitation.

This work has been submitted with an accompanying video which shows the procedure for mounting and removing the HEXOTRAC exoskeleton and demonstrates its tracking and force feedback functionalities.

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