A Wearable Exoskeleton for Hand Kinesthetic Feedback in Virtual Reality

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Abstract. This paper presents a novel two-fingers exoskeleton kinesthetic interaction in Virtual Reality (VR): the proposed design of the exoskeleton prioritizes the performance of the device in terms of low weight, good adaptability to different size of the human hand. This design made also the exoskeleton well wearable and allows strong force feedback which is an important parameter for a realistic kinesthesis of manipulated objects in VR.

Keywords: Haptic device · Wearable device · Kinesthetic feedback · Virtual reality

1 Introduction

Human beings are constantly interacting with objects on their daily life: this interaction is made possible through the manipulation and explorations of objects, devices and things, which are explored, touched and grasped by the hand of the user.

To perform such an interaction, multiple sensors are available on the human hands: the limbs, in fact, are equipped with a set of 'transducers' allowing the perception of position, temperature, roughness and movement and much more. These sensors are embedded within our limbs, muscles and skin [1]: from an anatomical viewpoint, the perception is induced by different *receptors* and *mechanoreceptors*, which provide kinematic and dynamic sensations, such as the Ruffini and Merkel cells and corpuscles.

Kinesthetic devices are wearable systems, which stimulate such receptors in order to provide a realistic 'kinesthetic' sensations in terms of movement and position. These devices are particularly useful when the end-user is interacting with a medical Virtual Reality (VR) environment allowing, for example, a remote surgical procedure. Typical kinesthetic devices are combining wearable sensors with mechanical components assuming the set of an exoskeleton or a robotic manipulator. They have been used for a variety of applications, including studies on human perception [2], development of training systems for MIS (Minimally Invasive Surgery) [3], rehabilitation devices [4, 5] and remote-control platforms [6].

Despite these progresses, the development of haptic devices for Virtual Reality systems requires a set of performance, which are not easy to be simultaneously achieved:

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these systems, in fact, should exhibit high accuracy, low inertia, high range of stiffness, combined with a small size of the equipment which is worn by the hand of the user. On the other side, the VR environment should require a minimum set of parameters to be controlled and interact with the haptic system. In this context, haptic exoskeletons are wearable force feedback devices that allow users to mechanically interact with the VR environment. They are becoming increasingly common and they are usually designed to guide the user's motion and give force feedback by attaching the exoskeleton to the human body, such as the user can control the position and movement of the fingers joints precisely [7, 8].

Exoskeletons for haptics may vary for their mechanical design, actuation system, and type of control. Force can be applied directly or indirectly through a transmission cable drive system. However, existing haptic exoskeletons cannot usually provide high fidelity force feedback in wearable setup. A high-quality haptic interface is typically characterized by low inertia and damping, high structural stiffness and absence of mechanical singularities. Other considerations in the design of wearable haptic exoskeletons are the space and weight limitation and the kinematic constraints induced by the human arm. The size of the overall design and mechatronics counterparts have to be smaller and lightweight to fit on human hand and therefore to increase the portability and flexibility, without affecting the dexterity of the hand.

Unlike other force feedback devices, haptic exoskeletons allow users to feel virtual and physical objects more naturally. This expands their applications in Virtual and Augmented Reality (VR, AR, respectively), medical and surgical training, teleoperation and others. Even though many researchers have developed different kinds of haptic exoskeletons, most exoskeletons with high fidelity force feedback restrain natural hand movement because of their complex mechanism. Moreover, the range and resolution of the force applied by the actuators should also be bigger enough to match with the human hand sensitivity.

Exoskeletons offer an intuitive method of actuating multiple Degress Of Freedom (DOFs) of the hand. These make them more valuable for application where the coupling of the force feedback devices with the fingers is needed. In this context, this paper presents the design and development of an exoskeleton for force feedback. The design of the exoskeleton focuses on the selection of a suitable kinematic, allowing the full reach of the finger's workspace, while combining under actuation with a proper wearable design.

2 Haptic Exoskeletons

The capability to be worn (i.e. the '*wearability*') of haptic devices broadened the application of haptic devices in a variety of new areas such as social interaction, health care, virtual reality, remote assistance, and robotics. However, smaller form factor and wearability bring a challenge in the design requirement of kinesthetic haptic devices. There are various types of hand exoskeletons developed for commercial and research purposes. For example, the *CyberGrasp* is a commercial haptic exoskeleton developed by CyberGlove Systems LLC, USA [9]. It uses electrical actuators placed on the dorsal side of the hand as drive system; low friction tendons are used to transmit forces from the actuators to the fingertips with a joint position resolution of 0.5° and a peak force of 12 N on the fingertip. CyberGrasp has relatively large weight, 350 g, which can cause fatigue if it is used for long hours. The mechanical bandwidth is also limited at 40 Hz due to the friction and backlash effect of the tendons. The *Rutgers Master II-ND* (RMII-ND) glove is another type of force feedback devices [10], which uses a direct drive actuation system with actuators placed on the palm. Compared to Cybergrasp, this exoskeleton weights less and is able to control four independent fingers thorough four pneumatic actuators, providing force feedback up to 16 N. Pneumatic actuators have also used in other exoskeletons presented [11–13]. Unlike other devices, the RMII-ND provide forces on the intermediate phalanx, leaving fingertips free to interact. Arata et al. [14] presented an exoskeleton mechanism, which is driven through large deformation of a compliant mechanism. The system is an underactuated mechanism which converts 1 DOF of linear motion into rotation of three finger joints causing extension and flexion. Similar mechanism with remote actuation system has been developed by Nycz et al. [15]. The remote actuation system used pull-push Bowden cable that transmits force from the back of the hand to the fingertip. This cable transmission system reduces the overall weight of the exoskeleton without affecting the functionality of the system.

Choi et al. [16] introduce the *Wolverine*, a mobile, wearable haptic device designed for virtual simulation of the interaction with rigid objects. This device renders a force directly between the thumb and the three fingers to simulate the grasp. The device can simulate grasping rigid bodies by leveraging low-power brake based locking sliders which can withstand up to 100 N force between each finger and the thumb. Time-of-flight sensors are used to track the position of each finger and an Inertial Measurement Unit (IMU) is used for orientational tracking.

Chiri et al. developed *Handexos*, a hand exoskeleton featuring a kinematic coupling with users joints [17, 18]. The self-aligning structure is made of revolute joint aligned with the user PIP and DIP joint, whereas the MCP joint uses a parallel chain made of two rotational and one linear DOFs. The mechanism uses a cable actuation system with an idle pulley to drive the joints of the exoskeleton. Iqbal et al. [19] developed a wearable mechanism which can provide forces up to 45 N at the proximal phalanx of the thumb and the index fingers. The design uses three revolute mechanisms (RRR). The same design has been revised considering multi-finger mechanism and overall wearability and performance [20, 21]. Othe authors presented a four-link serial mechanism which provides kinesthetic force feedback to the fingertip of the user [22]. Allotta and Conti et al. [23, 24] developed a 330 g *four-fingers parallel kinematic chain mechanism*. The device is grounded on the palm, and it can provide feedback in 1 DOF on the intermediate phalanx.

Achibet et al. [25] presented *Flexifingers*, a passive wearable exoskeleton with independent finger modules using bendable metal strips. The device provides kinesthetic feedback to four fingers up to 2.5 N. Each strip allows a 7.3 cm range of movement to the fingertip. Agrawal et al. [26] presented a wearable hand exoskeleton capable of bidirectional and independent joint torque control. The very light (80 g) mechanism uses *Series Elastic Actuation* (SEA) cables. The stiffness elements can be replaced to adjust for different users. Yang et al. [27] presented a jointless tendon-driven hand exoskeleton, which enables to couple the PIP and DIP movements as well as the MCP and PIP during flexion to replicate the natural finger motion during grasping.

3 Design

3.1 Optimization Criteria

In order to design a proper exoskeleton, different requirements and specifications that affect the performance and the ergonomics of the hand exoskeleton should be considered. Some primary design characteristics are:

- *Transparency* - A wearable exoskeleton haptic device should be a transparent interface to the remote and virtual environment, namely the user should be able to feel the interaction with the virtual objects as if this interaction occurs with the real ones.
- *Stiffness* - The maximum stiffness that can be achieved by the exoskeleton depend on the mechanical rigidity of the system and the achievable stability of the controller [28, 29]. Moreover, the device performance has a significant impact on the overall performance of the haptic display, irrespective of the used control algorithm.
- *Actuation* - The type of actuation and transmission systems are crucial factors in determining the performance. There are a variety of actuation technologies ranging from electric motors, hydraulic, pneumatic, magneto-rheological, electro-rheological, electroactive polymers, shape memory alloys, etc. This factor can compromise the portability of the system.
- *Force Feedback* - The maximum range or limits of force, velocity, and acceleration the haptic device can render should be enough for high force fidelity. The performance of an active force feedback control could suffer from actuator saturation to apply high forces or fast deceleration to display impulsive forces during interaction with hard contacts [30].
- *Wearability* - The kinematic design should accommodate different hand sizes without significant adjustment. The actuation system should allow a light-weight, portable and compact system. The device should be comfortable to wear. The way of attaching the device to the fingers should not obstruct the hand motions. There are basically two typical ways, namely (1) single location attachment and (2) multi-phalangeal attachment (see also Fig. 1).
- *Single point attachment* is simpler and provides haptic transparency by reducing unwanted internal forces between the mechanical structures and the finger phalanges.
- *Multiple attachments* to the phalanges provide an easier way of articulation of the finger and provide direct feedback forces to the attached phalanges. Such kind of design considers the number of DOF achievable by the hand and the size of the workspace reachable by the human hand.

Proper alignment of the exoskeleton joint and hand joint must be preserved during the use of these devices. There are various reasons which caused improper alignment of the exoskeleton joints from the finger joints: the first one is the inherently compliant mounting of the exoskeleton onto the hand, which leads to inaccurate positioning of the exoskeleton joints during movements. The other one is that the inter-subject variability of

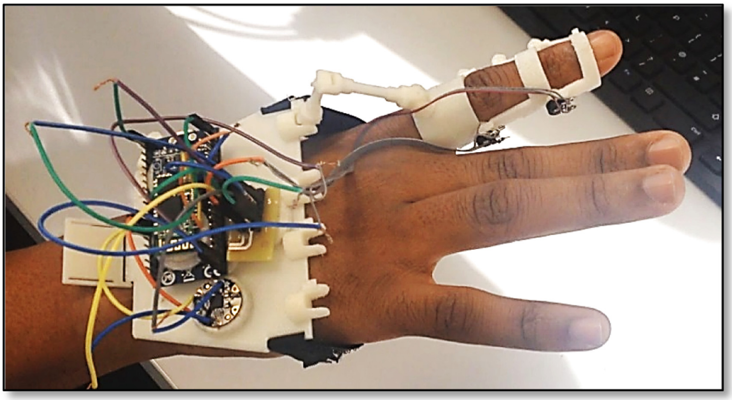

Fig. 1. A 3D printed index exoskeleton developed at the Robotic Laboratory of Liverpool Hope University.

the anatomical structure, size and shape of the hands requires an adjustable mechanism to align the joints.

3.2 Hand Kinematics

Understanding the kinematics of the human hand is essential to design a proper exoskeleton. For multi-phalangeal design, the joint degrees of freedom, joint ranges, and phalanx length should match the average human hand kinematic parameters.

Human hand grasping capability is amazing (Fig. 2). Its kinematics can be considered using a skeletal structure. The first link is the meta carpal joint, which is located in the palm. The base of each finger is connected to Metacarpus Phalangeal joints (MCP). Three phalanges, called the Distal Phalanx (DIP), the Middle Phalanx, and the Proximal Phalanx (PIP) are connected through the Inter-Phalangeal (IP) joints. The MCP joint connects the metacarpal and proximal phalanx. The PIP joint connects the proximal and middle phalanx, and the DIP joint connects the middle and distal phalanx. The thumb has only one IP joint. The motion of each finger includes flexion and extension as well as abduction and adduction.

The Index finger can be considered as three link mechanism with 4-DOF motion. However, human anatomy studies show that the motion of the DIP is naturally coupled with the PIP motion. Levangie et al. [32] shows that the maximum range of the index finger joints is 90° for the MCP, 100°–110° for the PIP, 80° for the DIP in flexion and extension movements, 40° for the adduction and abduction movements. This motion ranges vary for different fingers and different users according to the bone geometry and tendon and muscle structure of the hand. The thumb's kinematic is different from the other fingers. Unlike the index finger, the thumb has only three joints: the first two joints, MCP and DIP have revolute joints whereas the MC joint of the thumb can execute 3 DOF motion.

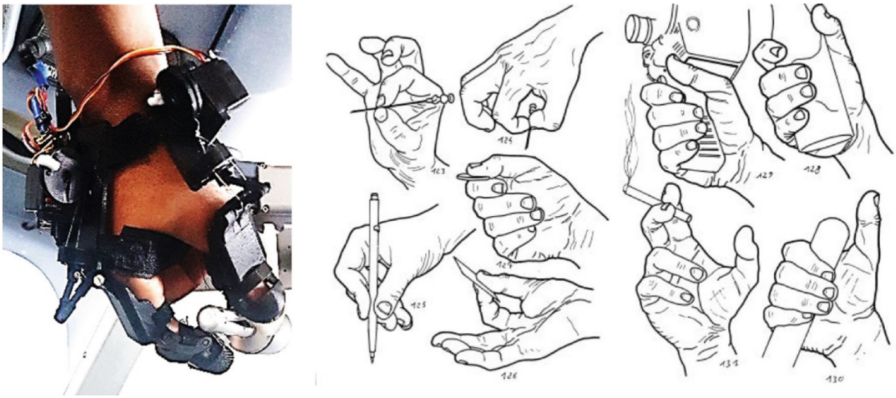

Fig. 2. Human hand grasping capability - from [31] - vs the proposed exoskeleton grasping performance.

3.3 Exoskeleton Design

According to the aforementioned optimization criteria and the human hand kinematics, the design and manufacturing of an underactuated, cable-driven hand exoskeleton is implemented. This process has required different steps as it is shown in Fig. 3. The Exoskeleton is designed to fit on two fingers of the human hand, i.e. on the index and thumb fingers which are the most used limbs to perform pinching and grasping. The design embeds lightweight links with low inertia. The overall system weighs around 120 g including the 3D printed mechanical system, the control electronics, and the actuators. Such a lightweight system will enable the user to use the exoskeleton without feeling fatigue.

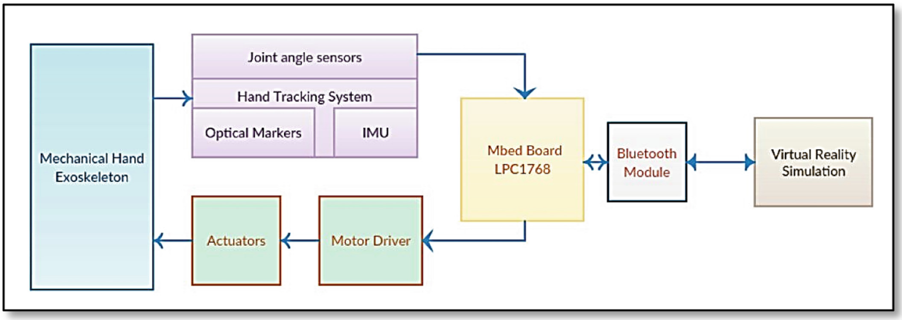

Fig. 3. Block diagram of the integration of the exoskeleton control and communication units.

a. Mechanical Design

In this section, the mechanical design of two fingers haptic hand exoskeleton that allows exerting forces on the index and thumb fingertip of the user is developed. The exoskeleton structure consists of a wrist and palm bracket, the palm mounting box, and the finger assemblies (Fig. 4). The wrist bracket and palm bracket are used to fix the exoskeleton on the hand, functioning as a ground for the finger assemblies. The palm is used to mount actuators and control electronics system. All finger lengths, joint positions, and widths of each finger were taken from measurements of an average size human hand. Velcro strap connected to each finger phalanx allows accommodating the different size of human fingers. A passive and adjustable MC joint mechanism is also used to fit the exoskeleton over hands of different size.

The complexity of the human hand structure makes it difficult to design an utterly similar hand exoskeleton, which controls the movement of the joints in all DOFs. Therefore, some consideration must be taken based on the physical assessment of the hand function. Based on some studies the finger adduction and abduction motion is not essential for achieving the critical hand functions including grasping and pinching [33]. Therefore, we do not include the abduction and adduction of the fingers on the design of the index finger exoskeleton. In addition, the index and the thumb finger joints have a limited range of motion (Table 2): therefore, the mechanism is designed to restrict unnecessary motions, apart from the natural movement of the finger joints. This is very important for the safety of the user, to reduce damage, which might be caused by a faulty and unstable control system.

The Exoskeleton fingers consist of three links corresponding to the DIP, MCP and PIP links. Rather than implementing a direct mechanical bar transmission (Fig. 1), a cable transmission is used to obtain a compact and lightweight assembly. Two cables are routed through the mechanical links, from the exoskeleton fingertip to the actuators on the hand, via a passive pulleys and bearings.

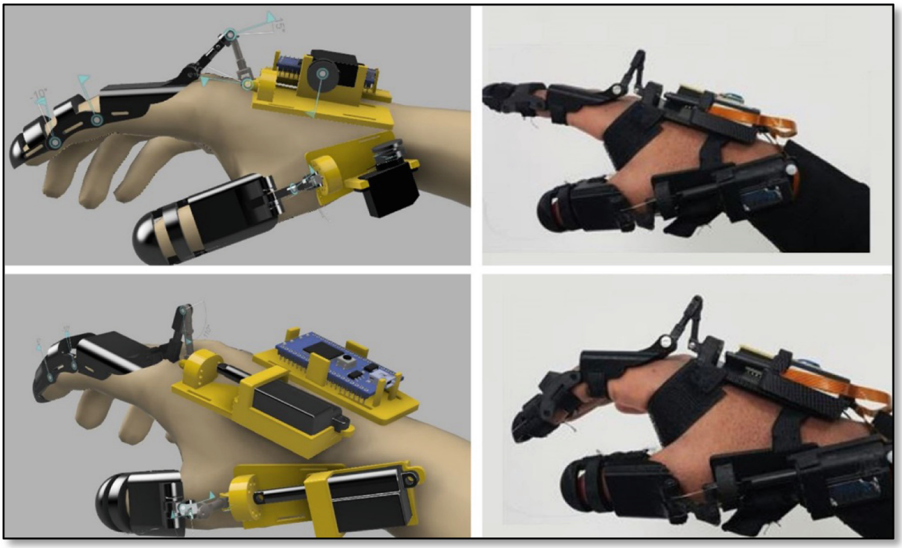

Fig. 4. 3D model and 3D printed haptic exoskeleton (left and right panels, respectively).

A first version of the hand exoskeleton was integrated where rotary servo motors (EMAX ES08MA-II) were used (Fig. 4). However, during some preliminary tests, tests revealed that these actuators do not have enough torque to resist vs the reactive force.

As a consequence, the actuation unit of a second version of the exoskeleton consists of two linear actuators (PQ12-P), one for index finger and another one for the thumb; each actuator is coupled with a cable driven system. The PQ12-P linear actuators weigh about 15 g and feature a stroke length of 20 mm with speed of 28 mm/s. The actuators can apply a maximum force of about 50 N (at 12 V). These forces exceed the maximum force which are needed to match a human hand maximum output force, which is around a value of 35 N. The commercial CyberGrasp haptic glove can output only up-to 12 N force. These actuators work as a linear servo, therefore, no external encoders are needed. The exoskeleton design is implemented with 3D printed parts which have been manufactured in PolyLactic Acid (PLA) material.

Table 1. Length of the exoskeleton *linkages*.

Linkages	Index [mm]	Thumb [mm]
L_1	52	0
L_2	58	45
L_3	21	25

b. Modelling

b.1. *Kinematic Model*

A simplified kinematic model of the finger is used to study the kinematic properties and trajectories of the hand. The index finger mechanism provides three rotary joints that allow extension and flexion of the finger. Accordingly, a planar model with three Revolute or Rotational joints (RRR) have been used as the kinematic model of the index finger. The Thumb also considers a planar model with two R joints. All the joints in the design use revolute pin connections. Extension and flexion are possible for both the index and the thumb mechanisms, whereas abduction and adduction movements are locked.

A schematic representation of the exoskeleton kinematic model is shown in Fig. 5. The revolute joint R_1 and R_2 mimic the PIP and DIP joints, respectively, while the third joint R_3 refers to the MCP joints. All three joints have parallel rotation axes forming a planar mechanism. The model follows the precise articulation of the index finger. The position of the exoskeleton's joint carefully matches the joint position of the human hand on the lateral side. The last MC joint uses two links to allow both rotation and translation of the finger assemblies with respect to the palm. Each joint is coupled with passive pulleys, which corresponds to the R joints. In addition, the exoskeleton is designed to keep the fingertip and the palm area free from additional tactile feedback. This also helps to reduce the weight of the overall system.

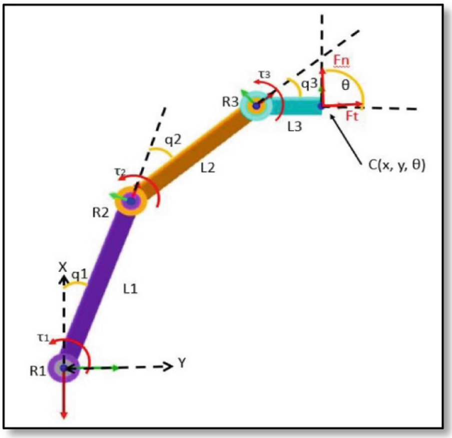

Fig. 5. The Kinematic model of the exoskeleton.

The human thumb kinematics is complicated because of the six degrees of freedom motion of the MC joint. In addition to the flexion, extension and adduction, abduction, the thumb performs a strategic opposition. Therefore, the thumb kinematics is simplified to allow the extension and flexion of the IP and MP joints. The abduction and adduction of the MC joint and the opposition movements are accommodated by the free passive motions of the elastic textile connector between the palm and thumb motor mounts.

Each finger of the exoskeleton can be modeled as planar and serial three link mechanism (Fig. 5), where the mount on the dorsum of the hand (i.e. the MC link) is considered as the ground link. The planar method ignores lateral movements of the finger, namely the adduction and abduction. Therefore, the overall exoskeleton device can be considered as an independent three-link (i.e. the index) and two-link (i.e. the thumb) mechanism, respectively. A separate thumb kinematic analysis is not necessary as the two links kinematic model of the thumb can be easily calculated by setting the first link length and the joint value of the index kinematic model to zero. Therefore, only the index finger kinematics is discussed.

The link parameters of both fingers are given in Table 1 and the joint constraints of the mechanism are reported within Table 2. These angular ranges are chosen to match the effective anthropomorphic articular ranges of the human hand.

The position and orientation of each fingertip are calculated using the forward kinematics equation. The position and orientation of the fingertip with respect to the MC link (ground) can be expressed using the 3×3 2D homogeneous transformation matrix, which consists of the rotation of each link with respect to the previous link, and the translation of each joint from the previous joint. It holds:

$$C = \mathrm{R}(\mathrm{q}_1)\ \mathrm{T}(\mathrm{L}_1)\ \mathrm{R}(\mathrm{q}_2)\ \mathrm{T}(\mathrm{L}_2)\ \mathrm{R}(\mathrm{q}_3)\ \mathrm{T}(\mathrm{L}_3) \tag{1}$$

Table 2. Anthropomorphic angular excursions of the rotational exoskeleton *joints*.

Joints	Index [°]	Thumb [°]
R_1	−30, +90	0
R_2	0, +110	0, +180
R_3	−5, +90	−5, +90

where

$$C = \begin{pmatrix} \cos(q_1+q_2+q_3) & -\sin(q_1+q_2+q_3) & x \\ \sin(q_1+q_2+q_3) & \cos(q_1+q_2+q_3) & y \\ 0 & 0 & 1 \end{pmatrix} \tag{2}$$

The 2D position and orientation of the fingertip can be extracted from the above transformation matrix. Precisely, the fingertip contact point $C\ (x, y, \vartheta)$ can be expressed by transforming the joint coordinates:

$$\begin{aligned} x &= L_1 \cdot \cos(q_1) + L_2 \cdot \cos(q_1+q_2) + L_3 \cdot \cos(q_1+q_2+q_3) \\ y &= L_1 \cdot \sin(q_1) + L_2 \cdot \sin(q_1+q_2) + L_3 \cdot \sin(q_1+q_2+q_3) \end{aligned} \tag{3}$$

and the rotational part is expressed as:

$$R = \begin{pmatrix} \cos(q_1+q_2+q_3) & -\sin(q_1+q_2+q_3) \\ \sin(q_1+q_2+q_3) & \cos(q_1+q_2+q_3) \end{pmatrix} \tag{4}$$

This component is similar to the rotation matrix occurring when a rotation of an angle of ϑ is performed around the z-axis. Therefore, the fingertip orientation can be expressed as:

$$\vartheta = q_1 + q_2 + q_3 \tag{5}$$

The forward kinematic equation can be generalized as $x = f(q)$ where x is position and orientation of the fingertip and q is the Lagrange joint variables. The derivative of this equation returns the Jacobian matrix, $J(q)$:

$$\dot{x} = J(q) \cdot \dot{q} \tag{6}$$

Accordingly, the linear velocity is expressed as a function of the Jacobian and of the joint velocities:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \end{pmatrix} \cdot \begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{pmatrix} \tag{7}$$

where it holds:

$$\begin{aligned} m_{11} &= -L_1 \cdot \sin(q_1) - L_2 \cdot \sin(q_1+q_2) - L_3 \cdot \sin(q_1+q_2+q_3) \\ m_{12} &= -L_2 \cdot \sin(q_1+q_2) - L_3 \cdot \sin(q_1+q_2+q_3) \\ m_{21} &= L_1 \cdot \cos(q_1) + L_2 \cdot \cos(q_1+q_2) + L_3 \cdot \cos(q_1+q_2+q_3) \\ m_{22} &= L_2 \cdot \cos(q_1+q_2) + L_3 \cdot \cos(q_1+q_2+q_3) \\ m_{32} &= -L_3 \cdot \sin(q_1+q_2+q_3) \\ m_{23} &= L_3 \cdot \cos(q_1+q_2+q_3) \end{aligned}$$

And, finally, then the rotational velocity can be expressed in function of the fingertip velocities, namely:

$$\begin{pmatrix} \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{pmatrix} = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{21} & m_{22} & m_{23} \\ 1 & 1 & 1 \end{pmatrix} \cdot \begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{\vartheta} \end{pmatrix} \tag{8}$$

b.2. *Workspace*

When exploring a free space in a remote or VR environment, the haptic device should not restrict the human users' motion (see also Sect. 3). Thus, the DOFs of the haptic device should match the natural ones of the human hand. According to Gruebler's formula, the mobility of the overall mechanism can be calculated as:

$$F = 3(n - l) - 2l - h \tag{9}$$

Where F is the total DOFs of the mechanism, n is the number of links (including the frame), l is the number of lower pairs (i.e. one DOF), h is the number of higher pairs (i.e. two DOF). According to the used kinematics, the results of Eq. (9) provide a 3-DOF mechanism for the index and a 2-DOF for the thumb, respectively. Enough workspace of the haptic device is also needed to achieve the desired motion which is achievable with the natural hand movement. The multi-link mechanism considered in this design is suitable for a multi-finger interaction and also it enables larger workspace for the haptic device. Accordingly, the 2D workspace for the index finger, as well as the joint trajectories, are shown in the Figs. 6 and 7.

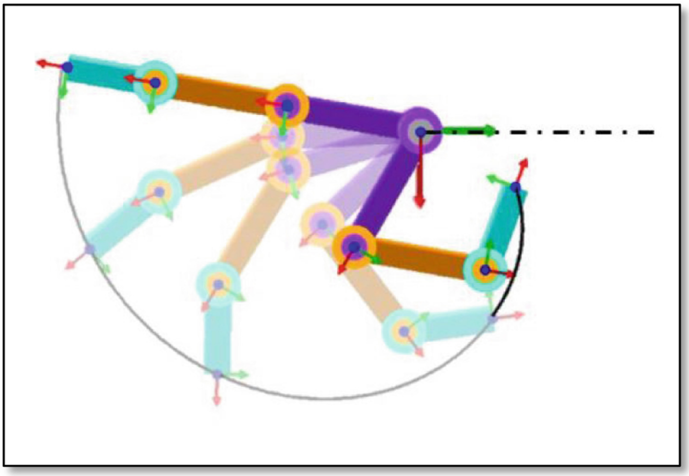

Fig. 6. Reachable workspace of the mechanism of the index finger.

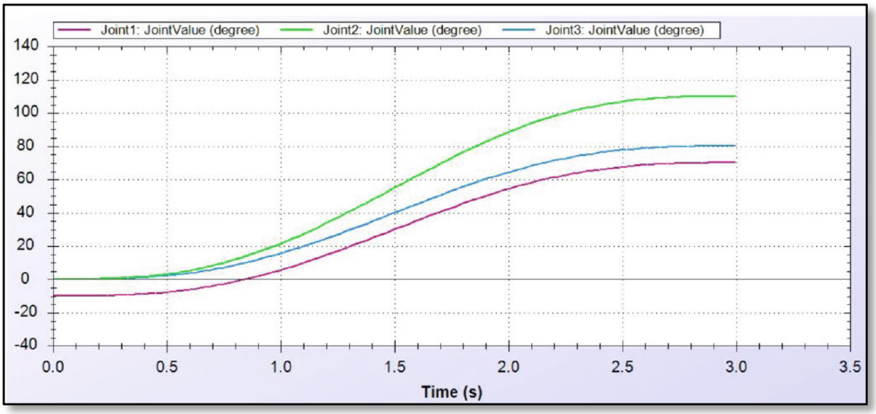

Fig. 7. Angular joint trajectories of the index finger mechanism - from the fully open configuration to the fully closed one.

b.3. *Actuation and Force Transmission*

An underactuated mechanism has been chosen to match the requirements such as a compact size, low weight, and low power system. The underactuated system allows having a number of actuators which is lower than the number of DOFs as performed with the hand. They also enable the exoskeleton mechanism to passively adapt to the finger structure.

Both the exoskeleton fingers are actuated via a cable transmission system, which is routed from the actuators on the palm to each joint of the finger up to the fingertip (Fig. 8). The cable transmission systems provide adequate power in order to also reduce the weight and inertia of the moving parts, and it allows remote actuation from the palm.

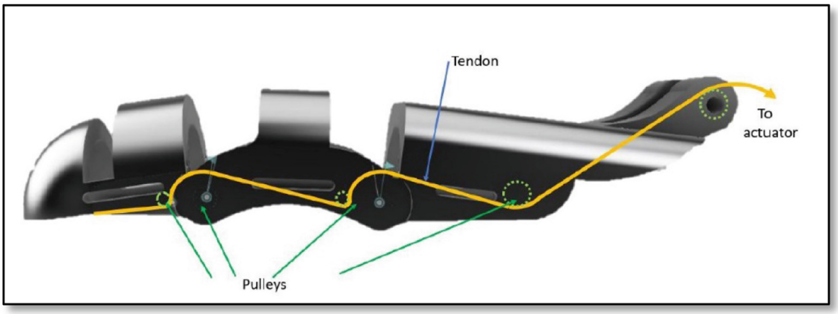

Fig. 8. The tendon and pulley mechanism of the index finger exoskeleton.

All revolute joints are driven by applying a tension force F to the cable which is wrapped around the finger joints of radius r. Assuming that the friction force is negligible, and that the cables are ideally rigid, the applied torque on each joint can therefore be expressed as a function of the radius of the pulleys and the tension force. Finally, an underactuated mechanism, with cable force transmission system, couples the joint torques with the cable tension F through the equation $\tau_i = F \cdot r_i$. The tension forces are also assumed to be constant for the same cable. This happens considering that the tension torque on the pulleys is negligible and the torque due to the pulley inertia is small. Unlike rehabilitation exoskeleton - which requires two cables for the extension and flexion movements - haptic exoskeleton requires a single cable to restrict the extension movement. The flexion can be passively performed not to restrict the natural movement of the finger (Fig. 8).

A DC motor actuation system pulls the cable. The haptic system needs either an active control of the cable position or should be back derivable so that the user can pull the cables with less amount of force. The haptic system should also be capable of delivering a maximum force that matches the human hand output force. Here, thanks to the adopted motors, the maximum thumb and finger force output is in the order of 35 N. The CyberGrasp, commercial force feedback device, can apply 12 N maximum output force, which is enough to provide a realistic force feedback sensation. As a consequence, in our design, a 10-12 N maximum force is considered.

4 Conclusions

In this paper, the design, and implementation of a wearable haptic exoskeleton is presented. A two-fingered (index-thumb) exoskeleton haptic device with force feedback function is developed. The exoskeleton consists of links corresponding to each phalange of the two finger which are connected with rotary joints. The determination of the position and orientation of each link relative to the previous one is solved by using a multi-body kinematics. The kinematic model also provides the necessary velocity and acceleration of the fingertip.

A VR system has been also developed around the exoskeleton: this VR component consists of a human hand physical model. The device can be used as a motion capture system, and as an input to a teleoperated control system, as a master device.

Even though the literature has presented different exoskeletons for haptics and rehabilitation purposes, there are still several problems which prevent those devices to be used in daily life [34]. Some of these constraints and limitations regard the fact that the exoskeletons are very large mainly because they use a direct drive system combined with mechanical links. Such a solution limits the natural movement of the end-user fingers, the joint angle positions, and the fingertip positions which may not properly measured. In this context the proposed haptic exoskeleton device should improve and by-pass some of these limitations thanks to its design.

We believe that the proposed device may have interesting application on rehabilitation and, in particular, in all medical application where the patient or the medical operator will benefit of haptic feedback.

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