(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 144 331 A1

(12) EUROPEAN PATENT APPLICATION

(43) Date of publication:
08.03.2023 Bulletin 2023/10

(21) Application number: **22194044.8**

(22) Date of filing: **06.09.2022**

(51) International Patent Classification (IPC):
A61H 1/02 *(2006.01)*

(52) Cooperative Patent Classification (CPC):
A61H 1/0277; A61H 2201/1215; A61H 2201/1418; A61H 2201/1614; A61H 2201/1635; A61H 2201/165

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
KH MA MD TN

(30) Priority: **07.09.2021 IT 202100023081**

(71) Applicants:
- **Politecnico di Milano**
  20133 Milano (IT)
- **Fondazione Istituto Italiano di Tecnologia**
  16163 Genova (IT)

(72) Inventors:
- **MOBEDI, Emir**
  16163 Genova GE (IT)
- **AJOUDANI, Arash**
  16163 Genova GE (IT)

(74) Representative: **Perani & Partners S.p.A.**
Piazza Armando Diaz, 7
20123 Milano (IT)

(54) A MOVEMENT ASSISTIVE DEVICE FOR THE ELBOW JOINT

(57) A movement assistive device (1) for the elbow joint, comprising: an actuation unit (20) provided with a motor (2); at least two arm garments (3,4,3',4') removably attachable to an arm of the wearer; at least one transmission cable (5, 5'); wherein the actuation unit (20) comprises: at least one elastic element (6) coupled with the motor (2) and configured to generate, under tension, an elastic force, the at least one transmission cable (5, 5') connecting the at least one elastic element (6) to the at least two arm garments (3,4,3',4') to apply the assistive torque to the wearer arm; at least one cam-spool mechanism (7,7') configured to elongate the at least one elastic element (6) as a function of human elbow torque/angle profile, wherein each cam-spool mechanism (7,7') comprises: a cam curve (8) with rotatable camshaft (9) to move a respective transmission cable (5, 5') around the cam curve (8); a roller (10) and a spool (11) provided with a slot (12), the spool (11) being coupled with the camshaft (9) though a roller (10) that can slide inside the slot (12); wherein the rotation axis of the camshaft (9) is decoupled and offset from the rotation axis of the spool (11).

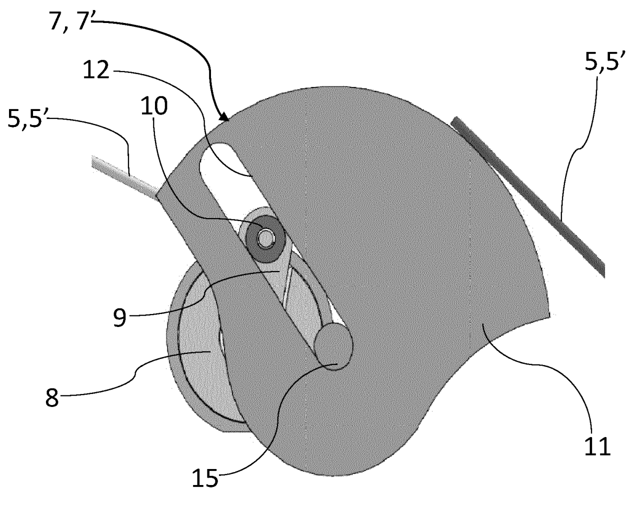


Fig. 2

Description

[0001] *The project leading to this application has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 871237.*

Technical field

[0002] The present invention is related to a movement assistive device for the elbow joint, wearable by a user for elbow effort compensation to be used especially in industrial applications, wherein the actuation system is remotely placed at the upper back of the user's body in order to reduce the weight of the device distributed across the human arm. The actuation system is cable-driven, compliant with human elbow torque/angle profiles, lightweight, and it is provided with energy storage material.

Background of the invention

[0003] Robotic exoskeletons are wearable mechanical devices designed to enhance the physical performance of the wearer, or to assist him/her to regain a weakened or lost functionality. To create active devices that are functional, yet also safe and ergonomic for the target applications, several requirements related to the wearer's comfort and safety, low mass/inertia, range of motion, easy wearability, and force range must be met.

[0004] To overcome the drawbacks of rigid exoskeletons, several alternative designs have been proposed. Soft exosuit do not constrain the motion of human joints since all interfaces and transmissions of the assistive forces to the human body are implemented through tendon driven mechanisms and elastic elements. The general idea of these devices is to locate the actuation system proximally and to transmit the force via Bowden cables. In this way, the load and the reflected inertia at the supported joints can be reduced during the execution of physical tasks, while increasing the comfort of the wearer. Due to their low weight, compact structure, and low power consumption ability, they have found several applications targeting the activities of daily living

[0005] It is known in the art to realize an assistive suit through the combination of fabrics attached to the human arm. The device is actuated using an agonist/antagonist motorized actuator with a planetary reduction drive located at the upper back of the human. It is also known to exploit the under-actuation principle to support the elbow joint of both arms using a single DC motor coupled with two pinion-bevel gear systems. The clutch and brake subsystems are used to enable an independent control of the two arms from the single actuation unit. These additional components and their integration have increased the complexity of the device, despite the fact that only one actuator was used for both elbow joints. Furthermore, since the implementation of this device does not include an elastic element in the actuation/transmission system, it cannot store energy during the flexion or extension movement of the elbow joint.

[0006] As another option, there are pneumatic actuation-based upper-limb exoskeletons to support the elbow joint. However, the air tank that is needed to actuate the device limits the mobility of the wearer especially in industrial applications.

[0007] It is known in the art a device wherein a DC motor is coupled with a clutch, brake and a bevel-gear system to support the elbow joint for both flexion and extension movements. However, bevel-gear mechanism causes a backlash, and this increases the uncertainties of the device in terms of modelling. Therefore, the control and calibration problem of the exoskeleton becomes difficult. Although this known exoskeleton has the capability to assist the two arms of a wearer using one actuation system through the under-actuation strategy, the mechanism does not include an elastic element. Because of this missing component, the force transmission from the assistive device to the human body cannot be accomplished in a compliant way. Hence, movement smoothness of the wearer can be effected negatively.

[0008] Known movement assistive devices are described in documents WO 2017/026943 A1, WO 2014/151584 A1, US 2020/000670 A1, WO 2018/165413 A1 and US 2020/261298 A1.

Scope of the invention

[0009] In this context, the technical object of the present invention is to provide a movement assistive device for the elbow joint which overcomes the drawbacks of the prior art.

[0010] Namely, the object of the present invention is to provide a movement assistive device for the elbow joint wherein the actuation mechanism takes into account the human elbow torque-angle profile. In more detail, the object is to provide an energy efficient, compliant, comfortable torque movement assisting device, which is able to reproduce the torque/angle characteristic profile of the elbow.

[0011] The specifically technical object and the specified aims are substantially achieved by a movement assistive device for the elbow joint comprising the technical characteristics described in one or more of the appended claims.

Advantages of the invention

[0012] The movement assistive device for the elbow joint described integrates a single motor coupled with an elastic bungee and a cam-spool mechanism to enable energy exchange during the elbow flexion movement, while allowing for free-motions during the extension of the joint.

[0013] Advantageously, experiments conducted on 3D printed functional prototypes suggest that the assistive elbow torque is effectively transmitted with an average

90% success for balancing a 5N payload, and the free-motion range of 108° is measured for both flexion and extension.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] Further characteristics and advantages of the present invention will appear more clearly form the description of a preferred embodiment of a movement assistive device for the elbow joint as illustrated in the enclosed drawings in which:

- Figure 1 is a back view of a user wearing the movement assistive device according to the present invention;
- Figure 2 is a perspective view of a detail of the movement assistive device of Figure 1;
- Figure 3 is a perspective view of another detail of the movement assistive device of Figure 1;
- Figure 4 is a schematic illustration of the working principle of the movement assistive device of Figure 1;
- Figure 5 is a schematic illustration of the method to identify the cam geometry to match the human elbow torque/angle curve;
- Figure 6 is a plot reporting the geometrically obtained cam lever length and the desired cam profile;
- Figure 7 is a plot reporting the stiffness profile of an example of endless ring type of bungee having a thickness of 5 mm and initial length of 55 mm and integrated in the movement assistive device according to the present invention;
- Figure 8 is a plot reporting the measured torque results of a fixed-end experiment carried out on the movement assistive device according to the present invention, and the desired toque curve to balance 5N load at the center of mass of a user forearm;
- Figure 9 is a plot reporting the selected pretension results to calibrate the movement assistive device according to the present invention to balance 5N load at the center of mass of a user forearm;
- Figure 10 is a plot reporting the estimated transmission cable force of a fixed-end experiment carried out on the movement assistive device according to the present invention, and the desired transmission cable force to balance 5N load at the center of mass of a user forearm;
- Figure 11 is a plot reporting the results of an open-end experiment carried out on the movement assistive device according to the present invention, wherein the right and left vertical exes of the plot reports the angular and linear position changes, respectively.

DETAILED DESCRIPTION

[0015] With reference to the attached figures, numeral 1 designates a movement assistive device 1 for the elbow j oint, wearable by a user for elbow effort compensation. In detail, the device 1 is a soft wearable movement assistive device.

[0016] The movement assistive device 1 for the elbow joint comprises an actuation unit 20 provided with a motor 2. Preferably, the motor 2 is a single DC motor.

[0017] Still preferably, the movement assistive device 1 comprises an upper back garment removably attachable to the upper back of the wearer's body and configured for housing at least the actuation unit 20.

[0018] Moreover, still preferably, the movement assistive device 1 comprises a battery pack housed in the upper back garment and configured to power at least the motor 2.

[0019] The motor 2 and the battery pack will not be described in more detail given that they are known to the skilled person.

[0020] In addition, the movement assistive device 1 comprises at least two arm garments 3, 4, 3', 4' removably attachable to an arm of the wearer.

[0021] Preferably, the at least two arm garments 3, 4, 3', 4' comprise two right arm garments 3,4 attachable to the right arm of the wearer and two left arm garments 3',4' attachable to the left arm of the wearer. Still preferably, the right arm garments 3, 4 and the left arm garments 3', 4' are each embodied as a bracelet wearable by the user.

[0022] More preferably, one of the right arm garments 3, 4 and one of the left arm garments 3', 4' are each wearable upstream of the respective elbow, while the other one of the right arm garments 3, 4 and the other one of the left arm garments 3', 4' are each wearable downstream of the respective elbow. In other words, during use of the movement assistive device 1 by a user, the right elbow of the user remains interposed between the right arm garments 3, 4 and the left elbow of the user remains interposed between the left arm garments 3', 4'.

[0023] Moreover, the movement assistive device 1 comprises at least one transmission cable 5, 5'. As it will be better explained herein after, the at least one transmission cable 5, 5' is configured to transfer the drive action of the motor 2 to the at least two arm garments 3, 4, 3', 4' to assist the movement of at least one user elbow.

[0024] Preferably, the at least one transmission cable 5, 5' comprises a right transmission cable 5 and a left transmission cable 5'. The right transmission cable 5 is configured to transfer the drive action of the motor 2 to the right arm garments 3, 4 to assist the movement of the right user elbow, while the left transmission cable 5' is configured to transfer the drive action of the motor 2 to the left arm garments 3', 4' to assist the movement of the left user elbow.

[0025] Still according to a preferred feature, the at least one transmission cable 5, 5' is a Bowden cable. More preferably, both the right transmission cable 5 and the left transmission cable 5' are each a Bowden cable.

[0026] Accordingly, the actuation unit 20 comprises at least one elastic element 6 coupled with the motor 2 and configured to generate, under tension, an elastic force. Preferably, the actuation unit 20 comprises one elastic element 6 for each arm of the user.

[0027] Preferably, the at least one elastic element 6 is a bungee. More preferably, the at least one elastic element 6 is an endless ring type of bungee with a diameter thickness of 5 mm and an initial length of 55 mm. Still preferably, each elastic element 6 is a bungee.

[0028] According to a preferred feature, the actuation unit 20 comprises at least one supporting mechanism. Preferably, the actuation unit 20 comprises one supporting mechanism for each arm of the user.

[0029] Still preferably, each supporting mechanism comprises a plate 17 provided with two supports 18. Each elastic element 6 is mounted on respective two supports 18. Still preferably, the motor 2 is coupled to each plate 17 with a ball-screw mechanism to move said plate 17 linearly.

[0030] It should be noted that, as each plate 17 is moved linearly by the motor 2, the respective elastic element 6 is elongated, namely the respective elastic element 6 generates an elastic force. It should also be noted that the elastic force generated by each elastic element 6 is configured to assist the movement of a respective user elbow.

[0031] Accordingly, the at least one transmission cable 5, 5' connects the at least one elastic element 6 to the at least two arm garments 3,4,3',4' to apply the assistive torque to the wearer's arm. Preferably, the right transmission cable 5 connects a respective elastic element 6 to the right arm garments 3, 4, while the left transmission cable 5' connects a respective elastic element 6 to the left arm garments 3', 4'.

[0032] In addition, the actuation unit 20 comprises at least one cam-spool mechanism 7, 7' configured to elongate the at least one elastic element 6 as a function of human elbow torque/angle profile. As it will be better explained hereinafter, the elastic force generated by a respective elastic element 6 is transferred to a respective cam-spool mechanism 7, 7' as an input elastic force.

[0033] Preferably, the actuation unit 20 comprises two cam-spool mechanisms 7,7', one for each arm of the user.

[0034] It should be noted that each cam-spool mechanism 7, 7' is configured to elongate a respective elastic element 6 as a function of a respective human elbow torque/angle profile.

[0035] In addition, each cam-spool mechanism 7, 7' comprises a rotatable camshaft 9 to move a respective transmission cable 5, 5'. More in detail, each cam-spool mechanism 7, 7' comprises a fixed cam with rotatable camshaft 9 to move a respective transmission cable 5, 5' around the fixed cam. The fixed cam is a cam curve 8. The cam curve 8 defines a part of the cam-spool mechanism 7, 7' having a curved shape, that is not a movable part. Each transmission cable 5, 5' is channeled in a respective first guide 81 of the cam curve 8. Namely, each elastic element 6 is connected to a respective camshaft 9 by a respective transmission cable 5, 5'.

[0036] In addition, each cam-spool mechanism 7, 7' comprises a roller 10 and a spool 11 provided with a slot 12. The spool 11 is coupled with the camshaft 9 through the roller 10 that can slide inside the slot 12. The roller 10 is configured to vary the input elastic force.

[0037] Each transmission cable 5,5' moves around a respective cam curve 8 via a respective roller 10.

[0038] Each transmission cable 5, 5' is also channeled in a respective second guide 111 of the spool 11.

[0039] It should be noted that, starting from a respective elastic element 6, each transmission cable 5, 5' is firstly channeled in a respective cam curve 8 through a respective camshaft 9 and then each transmission cable 5, 5' is channeled in a respective spool 11 to finally reach the respective two arm garments 3, 4, 3', 4'.

[0040] It should also be noted that, in each cam-spool mechanism 7, 7' the rotation axis of the camshaft 9 is decoupled and offset from the rotation axis of the spool 11. In other words, the rotation axis of the camshaft 9 is distinct, parallel and misaligned with respect to the rotation axis of the spool 11.

[0041] According to a preferred feature, each cam-spool mechanism 7, 7' comprises an eccentric shaft 15 operatively coupled with the respective spool 11 and the respective camshaft 9 . Since the rotation axis of the eccentric shaft 15 is parallel to the rotation axis of the camshaft 9, the spool 11 performs its rotation parallel to the rotation axis of the camshaft 9 as well. It should also be noted that, the incorporation of the eccentric shaft 15 achieves a reliable bedding for the spool 11. In fact, due to the geometry of the eccentric shaft 15, the working range of the camshaft 9 increases, since the roller 10 can approach the rotation center of the spool 11 for small degrees.

[0042] Still according to a preferred feature, each cam-spool mechanism 7, 7' comprises a flange 16 to align the respective spool 11 and the respective eccentric shaft 15 on the same axis.

[0043] According to a preferred feature, the actuation unit 20 comprises a control unit for driving the motor 2. Said control unit is in signal communication with an external device. The control unit is configured to activate the motor 2 so that the motor 2 can generate the drive action upon receival of a command signal by the external device.

[0044] It should be noted that to design the movement assistive device 1, the desired torque trend of the elbow joint to balance a load at hand was firstly calculated. More in details, a bungee has been selected as the elastic element 6, to provide an intrinsically soft interaction between movement assistive device 1 and the elbow, and to form a mechanical filter against dynamic uncertainties. This choice is due to the intrinsic damping, and the high energy storage density due to a larger elongation possibility. To adapt the S-shaped force profile of the bungee to the desired torque profile of the human elbow, which is sine shaped, the cam-spool mechanism 7, 7' described above has been designed.

[0045] With particular reference to Fig. 4, the movement assistive device 1 was firstly designed by estimating the required elbow torque around the rotation center of the user elbow. Assuming that a given payload is held at a center of the mass of the forearm of the user, the required elbow torque to support the payload is given by:

$$\tau = W_L \sin\theta\,(d)$$

wherein:

τ is the required elbow torque;
W_L is the payload;
θ is the elbow angle;
d is the length of the forearm of the user.

[0046] Subsequently, the desired force on the transmission cable 5, 5' to apply the above calculated torque can be calculated as follows:

$$F_d = \frac{\tau}{L\,cos\,\gamma}$$

Wherein:

F_d is the desired force on the transmission cable 5,5';
τ is the calculated elbow torque;
L is the length represented in Fig.4;
and γ is calculated as follows:

$$\gamma = 90 - \alpha - (\theta/2)$$

wherein:

α is the angle represented in Fig.4;
θ is the elbow angle.

[0047] It should be noted that the maximum value for the elbow angle has been set at 116°. Given said value, the necessary transmission cable 5, 5' length (l_f) for the flexion and the extension movements has been approximately estimated as 178 mm using the following formula:

$$l_f = \sqrt{2(a^2 + b^2)(1 - \cos\varphi)}$$

Wherein:

a is the forearm width;
b is the distance between the position point of the arm garments 3,4, 3', 4' on the user arm and the rotation center of the user elbow;
φ is the angle represented in Fig.4.

[0048] It should be noted that the transmission cable 5, 5' length has been estimated by considering the forearm width equal to 50 mm, the distance between the position point of the arm garments 3,4, 3', 4' on the user arm and the rotation center of the user elbow equal to 100 mm and the forearm length equal to 150 mm.

[0049] It should also be noted that the design of the cam-spool mechanism 7, 7' considers two objectives. First of all, the cam-spool mechanism 7, 7' shall permit a transmission cable 5, 5' length of 178 mm to be wrapped/released during the flexion/extension movement. Then, the cam-spool mechanism 7, 7' should provide a variable cam lever length h that shapes the torque/angle profile generated by the movement assistive device 1 to that of the human elbow.

[0050] With particular reference to Fig. 5, the cam 8 and the user elbow are supposed to perform equivalent angles, namely the elbow angle indicated as θ. In this proof-ofconcept design, R sin θ curve is drawn for value of the elbow angle equal to 116° and assuming R equal to 40 mm to obtain the cam 8 profile, as visible in Fig. 5. This graph is divided by four equal segments of angle θ to explain the geometrical derivation of the cam 8, and the y axis of each θ segment displays the cam 8 radius that is aimed to be matched with the sinusoidal curve. The circles, whose radii vary by R sin θ are drawn for each segment of angle θ with respect to the center, indicated as O_1 in Fig. 5. The intersections of circles and divided lines give the point of cam 8 curve, which is a circle (having a center indicated as O_2 in Fig.5) that is shown with black points in Fig.5. Six points and two radii (indicated as R_1 and R_2 in Fig. 5 respectively) are illustrated.

[0051] The geometrically obtained cam lever length h and the desired cam 8 profile are reported in Fig. 6.

[0052] To link the cam 8 curve with the human arm and the bungee, it has been implemented the cam-spool mechanism 7, 7' having rotation axis of the cam 8 and the spool 11 separated. As described above, the cam 8 is fixed, while the transmission cable 5,5' rotates around it via the roller 10, which is housed in the slot 12 opened in the spool 11. Namely, the transmission cable 5,5' is moved around the cam 8 curve trough the camshaft 9.

[0053] It should be noted that the rotation axis of the camshaft 9 and the rotation axis of the spool 11 are decoupled in order to permit to match the human elbow angle with the corresponding cam lever length h. In this way, the spool 11 rotation is in 1:1 relationship with respect to the elbow angle while the camshaft 9 rotates twice as much as the spool 11. As a result of this coordination, the desired cam lever length h can be obtained without adding an extra cable transmission to the movement assistive device 1.

[0054] It should also be noted that, the proposed movement assistive device 1 enables the following two functionalities. Under no payload conditions when the elbow joint needs to move without any constraints the roller 10 performs a linear motion in the slot 12, adapting to the elbow rotation and varying the cam lever length h continuously around the spool 11 rotation axis. In this case, the bungee is tensioned only to avoid relaxation on the transmission cable 5, 5' (to achieve high transparency).

[0055] At the same time, it should also be noted that, when assistance is needed, the human can take the load with an almost fully extended arm. This condition requires a higher elastic force generated by the movement assistive device 1 to counteract the load. As the human flexes the elbow, the elbow angle and the cam lever length h increase (as can be seen in Fig.6), which results in applying less pretension on the elastic element 6. In other words, the initially stored elastic force can be adjusted mechanically as a function of the cam lever length h during the flexion movement. This is, in fact, one of the significant reasons why the cam-spool mechanism 7, 7' is integrated into the movement assistive device 1.

[0056] To calculate the spool 11 radius and the ball-screw stroke, the diameter of the camshaft 9 has been set equal to 40 mm, while the maximum elbow angle has been considered equal to 116°. Using these parameters, the spool 11 radius has been computed as follows:

$$r_{spool} = \frac{l_f}{\theta_{max}}$$

[0057] Wherein:

r_{spool} is the spool 11 radius;
lf is the transmission cable 5, 5' length (l_f) for the flexion and the extension movements ;
θ_{max} is the maximum elbow angle.

[0058] Additionally, the transmission cable 5, 5' length wrapped around the camshaft 9 is calculated to determine the necessary stroke in the ball-screw transmission of the actuation unit 20. As discussed before, the rotation angle of the camshaft 9 is twice the spool 11 rotation angle.

[0059] Moreover, according to the geometrical derivation of the cam 8 curve, the radius of the cam 8 is equivalent to half of the diameter of the camshaft 9. Therefore, the ball-screw stroke is calculated as follows:

$$S = (2\theta_{max})(R/2);$$

[0060] Wherein:

S is the ball-screw stroke;
θ_{max} is the maximum elbow angle;
R is the diameter of the camshaft 9.

[0061] Considering an additional 20 mm tolerance for the elongation of the bungee, the ball-screw stroke is selected as 100 mm.

[0062] It should be noted that, using the movement assistive device 1 described a user is allowed to perform pronation and supination movements.

[0063] It should also be noted that, the elastic element 6 integrated in the movement assistive device 1 provides an intrinsically soft interaction between the actuation unit 20 of the movement assistive device 1 and the limb of the human body, where the actuation output is applied, and forms a mechanical filter against dynamic uncertainties, absorbing sudden motions or possible control issues, protecting both the actuation of the movement assistive device 1 as well the human subject from feeling such dynamic force transients. Furthermore, the elastic element 6 enables energy storage and recycling, which leads to the reduction of energy consumption.

[0064] As already described, the elastic element 6 is preferably a rubber-type elastic element in the form of a bungee cord. This selection choice was driven by a number of performance characteristics of this type of elastic element, including its large elongation, intrinsic damping feature, lightweight property, and low sensitivity in mechanical misalignment. Advantageously, this type of elastic element also permits a variety of configurations such as U shape.

[0065] Still advantageously, as already described, a mechanical constraint, which leads to limit the motion range of the elbow joint, was detected in the design stage of the cam-spool mechanism 7, 7'. Thanks to the developed eccentric shaft 15, the working range of the elbow joint is optimized to be between 9°-116°, which is appropriate for manipulation tasks in industrial applications.

[0066] In the following section two experiments carried out on the movement device 1 will be described.

VALIDATION EXPERIMENTS

[0067] Two experiments under fixed-end and open-end conditions were carried to validate the functionality of the movement assistive device 1 described.

[0068] In the fixed-end experiment, a first prototype of a user elbow is manufactured considering the human forearm dimensions and the location of the arm garments 3, 4, 3', 4' on the user arm. Said first prototype is made of plastic and several holes are opened on this first prototype with 15° resolution to measure the torque variation in seven test angles.

[0069] In the open-end experiment, a second plastic prototype of a user elbow is fabricated similarly to the first prototype. In said open-end experiment, a first encoder is attached to the second prototype, while a second encoder is coupled with the flange 16 to compare if spool 11 and the second prototype achieve the same rotations.

[0070] In the fixed-end experiment, the first prototype is coupled rigidly with an F/T sensor (ATI-Mini45, SI 145-5), and they are both fixed to a table through apparatus. Center pins and screws are used to engage the first prototype and F/T sensor so that the applied assistive force can be measured in different test angles. In the open-end experiment, the second prototype is free to rotate, and the aim is to measure the motion range of the movement assistive device 1.

[0071] A motor driver and a data acquisition card communicating through EtherCAT at 1kHz is used to control the movement assistive device 1. A PID regulator is used through MATLAB/Simulink Real-Time® interface to drive the motor 2 in power unit. The resultant linear position error on the ball-screw mechanism was detected between ±0.15 mm. Additionally, a 0.5 ± 0.1 Nm bias torque is maintained with the help of the movement assistive device 1 in the fixed-end experiment to avoid relaxation on the transmission cable 5, 5' and compensate for any backlash in the assembly.

Fixed-end experiment

[0072] The force profile of the bungee is evaluated by tensioning the bungee between 0 - 10 mm (0.5 mm position increment) in each predetermined elbow test angle (15 - 105°) and measuring the resultant torque around the rotation center of the first prototype of a user elbow.

[0073] These data are used to estimate the desired force on the transmission cable 5, 5' and the profiles of said force are reported in FIG.7 . Furthermore, the average values of those estimated forces are calculated for each pretension value, and the resulting shape is demonstrated as "average" in the same figure. Finally, the same bungee is elongated (similar pretensions as the first prototype) using another tension machine. The measured force profile are reported as "desired" in FIG.7.

[0074] According to the results shown in Fig.7, the force profiles slowly rise in the beginning, then the trend sharply increases until 4% elongation, while for larger elongations the slope of the increment reduces. It is obvious that the differences in the force shapes among the test angles are insignificant, which indicates that the assembly of the components, transmission cable 5, 5' connections and the force estimation are achieved with minimal error. There is also an almost constant shift between desired and average force curves in most of the entire pretension points. This originates from the uncertainties of the plastic parts, such as stretching, manufacturing errors, as well as the friction in the transmission cable 5, 5'.

[0075] Next, the movement assistive device 1 is tested to demonstrate the strength of the cam-spool mechanism 7, 7'. To implement that, first, the desired torque profile, which is expected to be delivered by the assistive device 1, is calculated by considering a payload of 5N. Then, the first prototype of a user elbow is configured and fixed mechanically in all the test points (15° - 105°) one by one, and the spool 11 is rotated through the motor 2 to the same position as that of the first prototype. Subsequently, the bungee is tensioned, starting from 1-10 mm (1 mm position increment) with the help of the motor 2 in each test angle. Every pretension is repeated three times (standard deviation ≈ 0.1 - 0.0006). Finally, the average values of those data are extracted from the bias torque, and they are graphically represented in the plot reported in Fig.8.

[0076] As can be seen from the plot reported in Fig.8, there is a nonlinear increment as the elbow angle increases, which is an expected result based on the trend of the cam lever length. However, there are fluctuations for 1 mm elongation curve. The reason is that since the transmitted force for that pretension is lower than others, the small relaxations on the transmission cable 5, 5', backlash between the assembled components, and frictions could not be compensated precisely.

[0077] Furthermore, according to the trend of the cam lever length h (as reported in Fig. 6) it is expected to observe a slight reduction on the torque results between 90° to 105° (as can be seen in the plot reported in Fig.8). The reason why this behavior could not be detected is that the cam lever length h difference between those two test angles is very low, and seven test points are not adequate to validate the output torque of the movement assistive device 1 completely. Particularly, as can be seen in the plot reported in Fig.8, the increment ratio of the torque trends between 1 - 4 mm elongations is significantly higher than that of the other pretensions. The aforementioned increment ratio is directly related to the stiffness curve of the bungee, which follows a sharp increase until 4 mm elongation, and then the slope of the force response reduces (as can be seen in the plot reported in Fig.7).

[0078] In the final step, the closest torque values to the desired ones are selected, and the corresponding pretension values are defined as "selected pretensions" for the calibration of desired torque profile. Those selected pretensions are applied to first prototype of a user elbow in all the test angles. The trend of the results are represented in the plot reported in Fig.9.

[0079] Besides, it is observed that there is an angular position shift (±4°) between the spool 11 and the elbow, originating from the difficulty of precise position initialization of the first prototype of a user elbow and spool 11. Moreover, as discussed before, when the elbow angle is increased, the cam lever length h is supposed to rise as well, resulting to lower elastic force. This behavior is clearly observed because the selected pretension values are significantly higher for 15° than 105°.

[0080] Finally, the plot report in Fig.10 shows the desired force on the transmission cable 5, 5', which is calculated by using the measured torque values.

Open-end experiment

[0081] In the Open-end experiment, a 0.5 kg load is mounted on the second prototype of a user elbow, and the motor 2 is driven to achieve the selected ball-screw stroke for the flexion and extension movement. It can be seen in the plot reported in Fig.11 that the position difference between the spool 11 and the elbow is very low (RMS =6.14°), which validates the proposed design concept. In addition, the measured angular position data verify the targeted kinematic working range of the elbow, which varies between 9 - 116° (108°).

Claims

1. A movement assistive device (1) for the elbow joint, comprising:

   - an actuation unit (20) provided with a motor (2);
   - at least two arm garments (3,4,3',4') removably attachable to an arm of the wearer;
   - at least one transmission cable (5, 5');

   wherein the actuation unit (20) comprises:

   - at least one elastic element (6) coupled with the motor (2) and configured to generate, under tension, an elastic force, the at least one transmission cable (5, 5') connecting the at least one elastic element (6) to the at least two arm garments (3,4,3',4');
   - at least one cam-spool mechanism (7,7') configured to elongate the at least one elastic element (6),

   characterized in that each cam-spool mechanism (7,7') comprises:

   - a cam curve (8) with rotatable camshaft (9) to move a respective transmission cable (5, 5') around the cam curve (8);
   - a roller (10) and a spool (11) provided with a slot (12), the spool (11) being coupled with the camshaft (9) though a roller (10) that can slide inside the slot (12);

   wherein the rotation axis of the camshaft (9) is decoupled and offset from the rotation axis of the spool (11).

2. Movement assistive device (1) according to claim 1, comprising an upper back garment removably attachable to the upper back of the wearer's body and configured for housing at least the actuation unit (20).

3. Movement assistive device (1) according to claim 2, comprising a battery pack housed in the upper back garment and configured to power at least the motor (2).

4. Movement assistive device (1) according to any of the previous claims, wherein the at least two arm garments (3,4,3',4') comprise two right arm garments (3,4) attachable to the right arm of the wearer and two left arm garments (3',4') attachable to the left arm of the wearer.

5. Movement assistive device (1) according to claim 4, wherein the motor (2) is a single DC motor.

6. Movement assistive device (1) according to claim 5, wherein the actuation unit (20) comprises two cam-spool mechanisms (7,7'), one for each arm of the user.

7. Movement assistive device (1) according to any of the previous claims, wherein the at least one elastic element (6) is a bungee.

8. Movement assistive device (1) according to any of the previous claims, wherein the at least one transmission cable (5, 5') is a Bowden cable.

9. Movement assistive device (1) according to any of the previous claims, wherein the actuation unit (20) comprises a control unit for driving the motor (2).

10. Movement assistive device (1) according to any of the previous claims, wherein each cam-spool mechanism (7,7') comprises an eccentric shaft (15) operatively coupled with the respective spool (1) and the respective camshaft (9).

11. Movement assistive device (1) according to claim 11, wherein each cam-spool mechanism (7,7') comprises a flange (16) to align the respective spool (11) and the respective eccentric shaft (15) on the same axis.

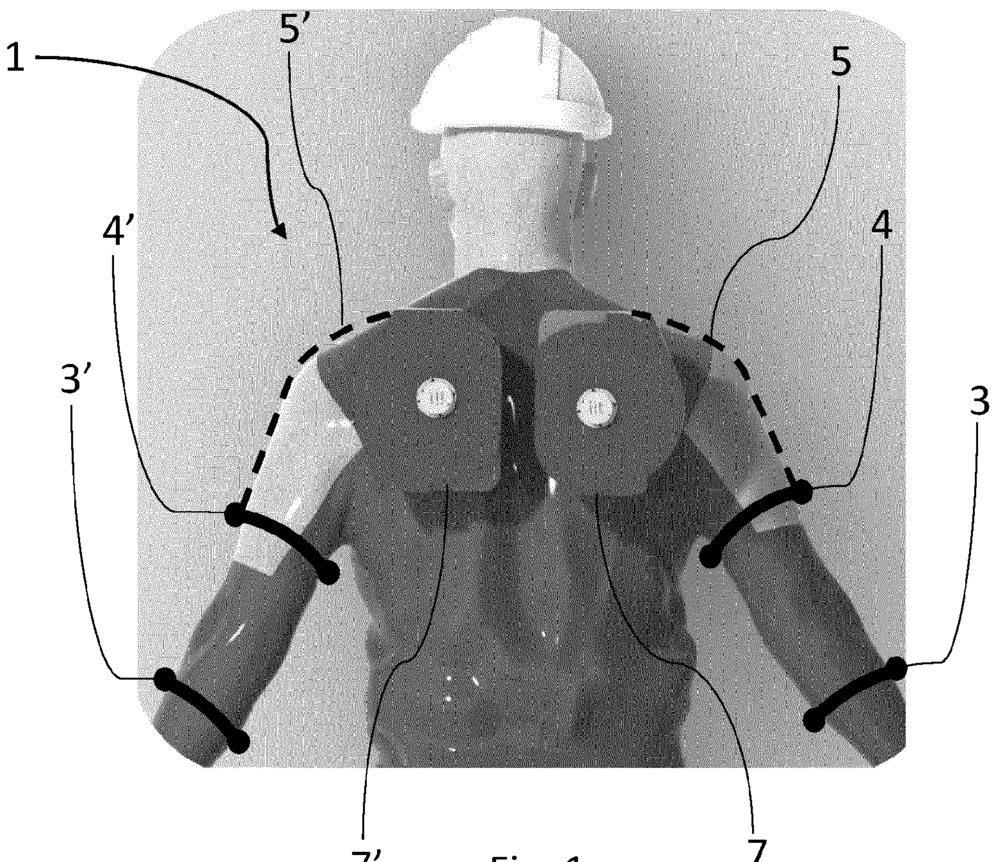


Fig. 1

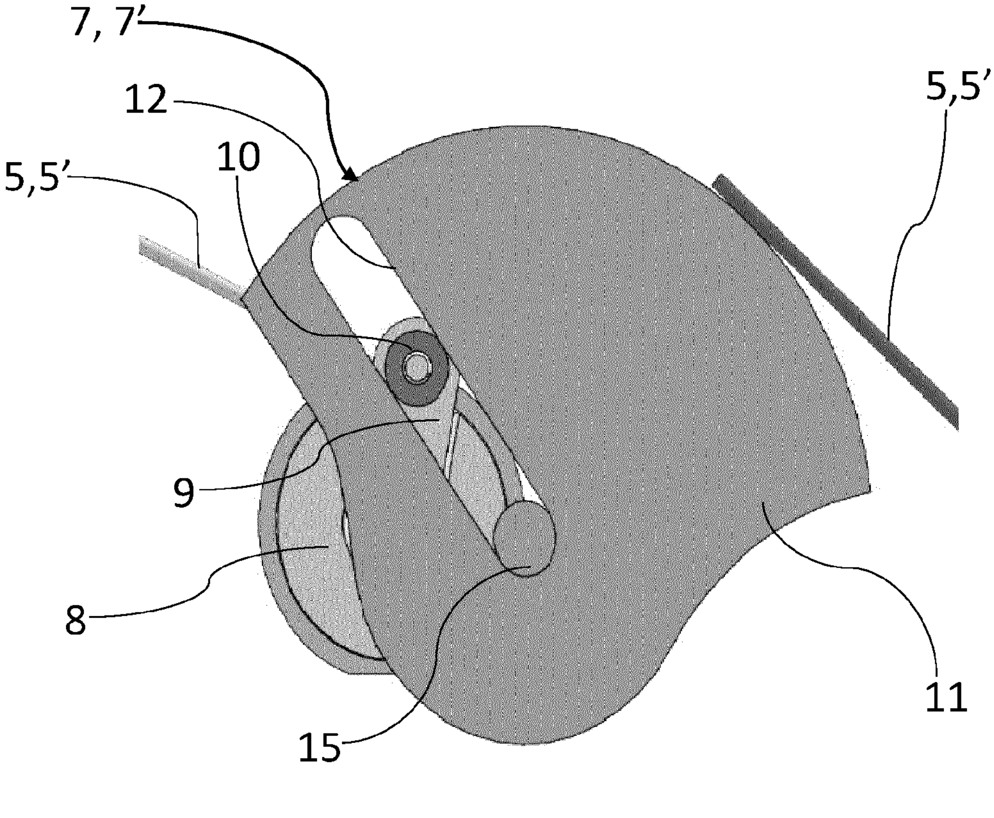


Fig. 2

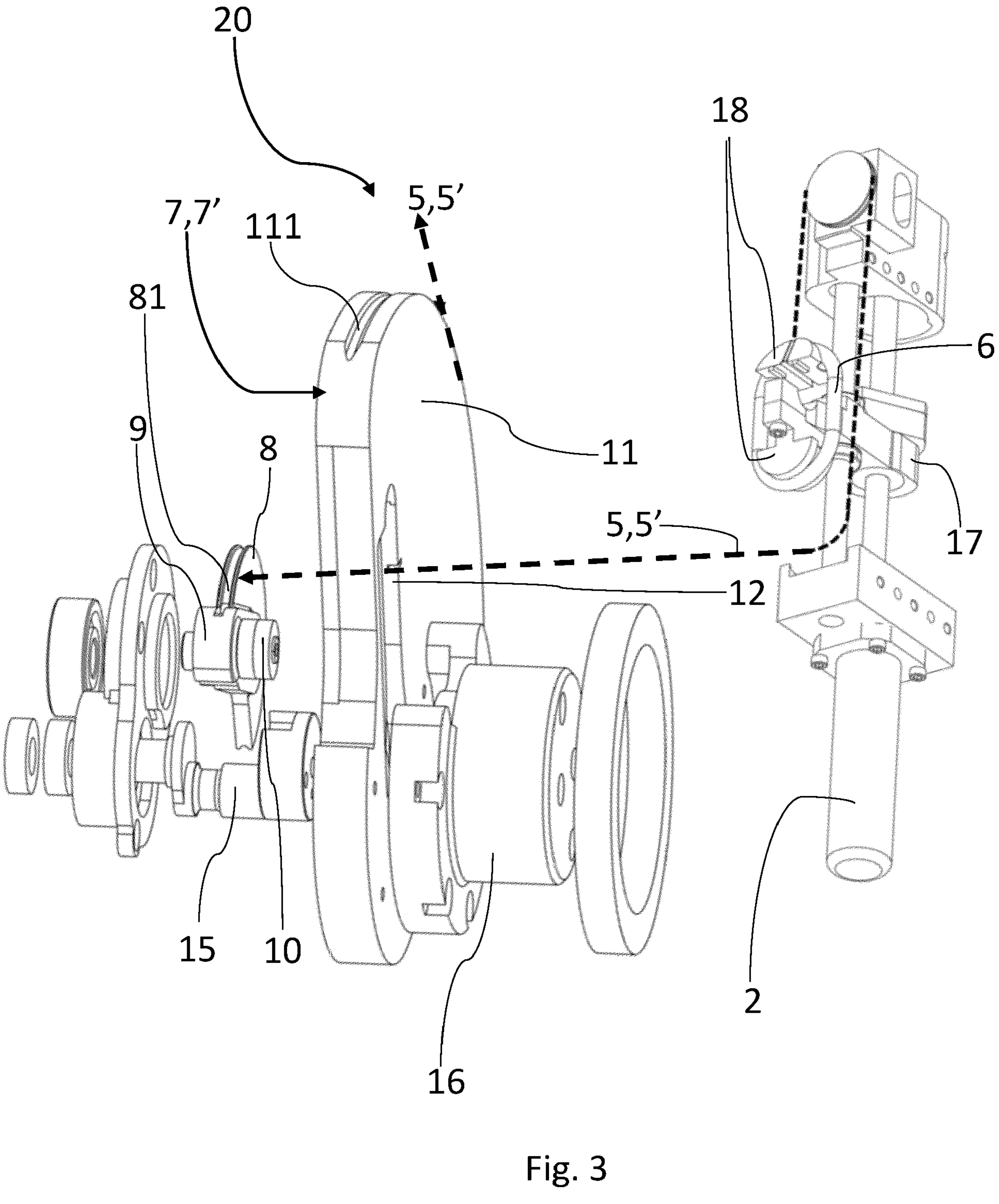
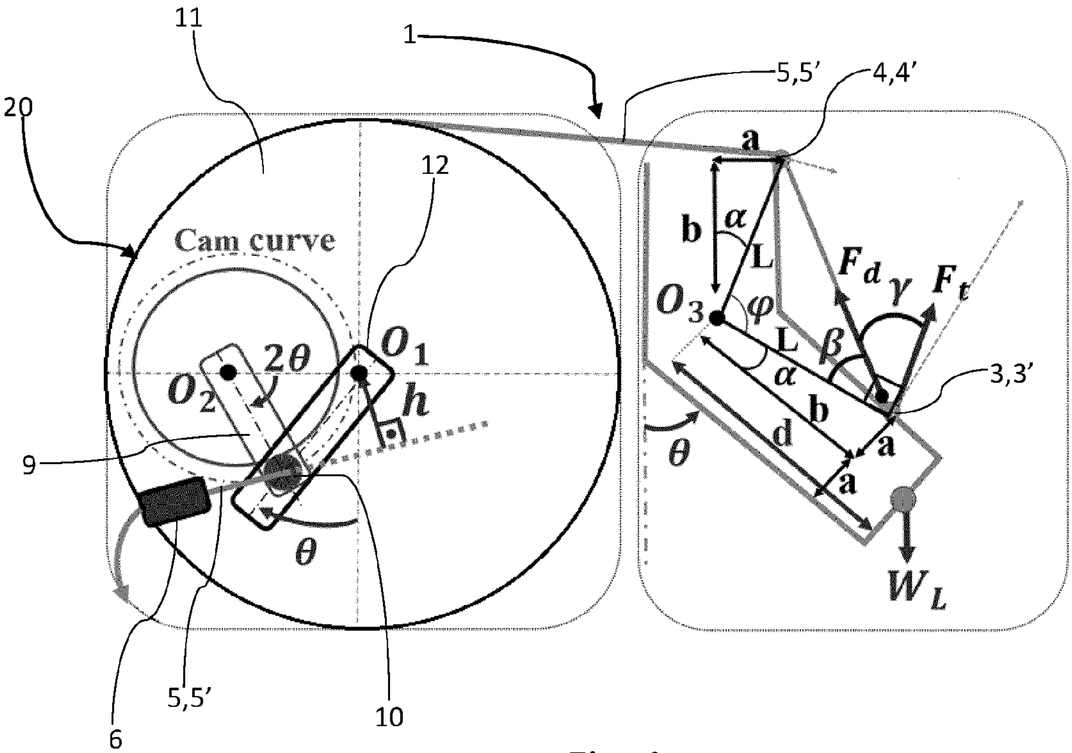
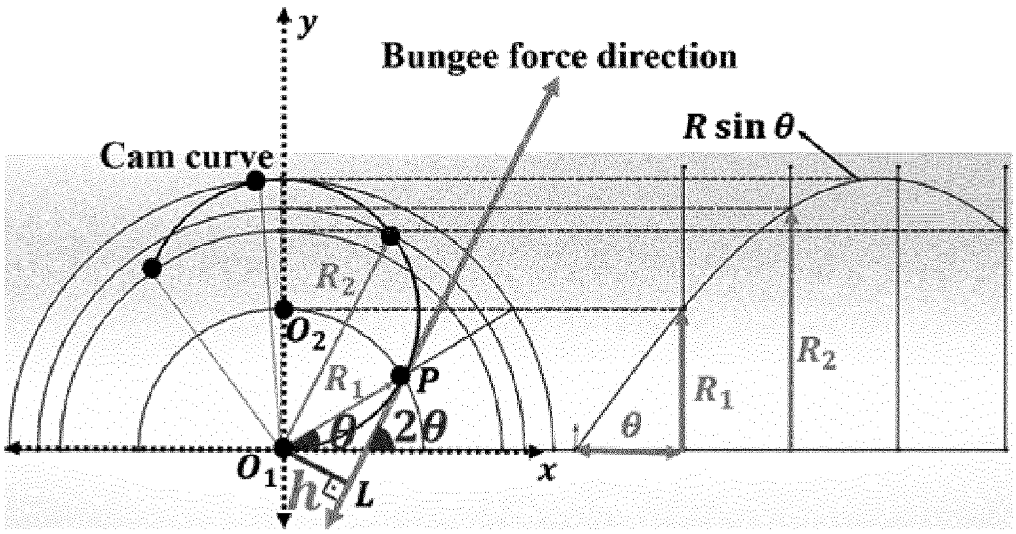


Fig. 3



1
11
20
12
5,5'
4,4'
Cam curve
a
b
α
L
F_d
γ
F_t
O_3
φ
β
O_1
2θ
O_2
h
3,3'
9
d
θ
W_L
6
5,5'
10

Fig. 4



y
Bungee force direction
R sin θ
Cam curve
R_2
O_2
R_1
P
θ
2θ
O_1
h
L
x

Fig.5

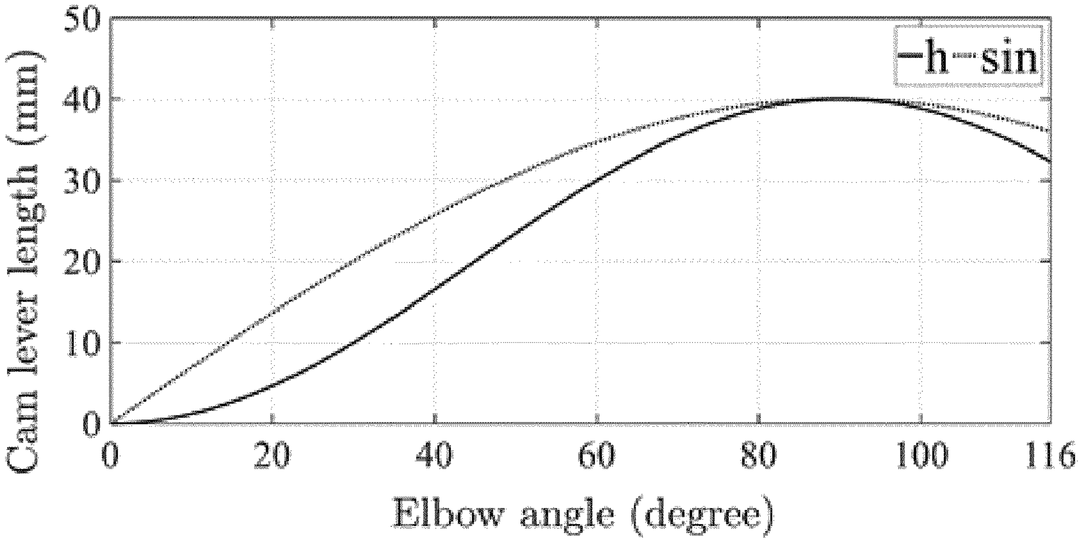

50
40
30
20
10
0
Cam lever length (mm)
0
20
40
60
80
100
116
Elbow angle (degree)
h
sin

Fig.6

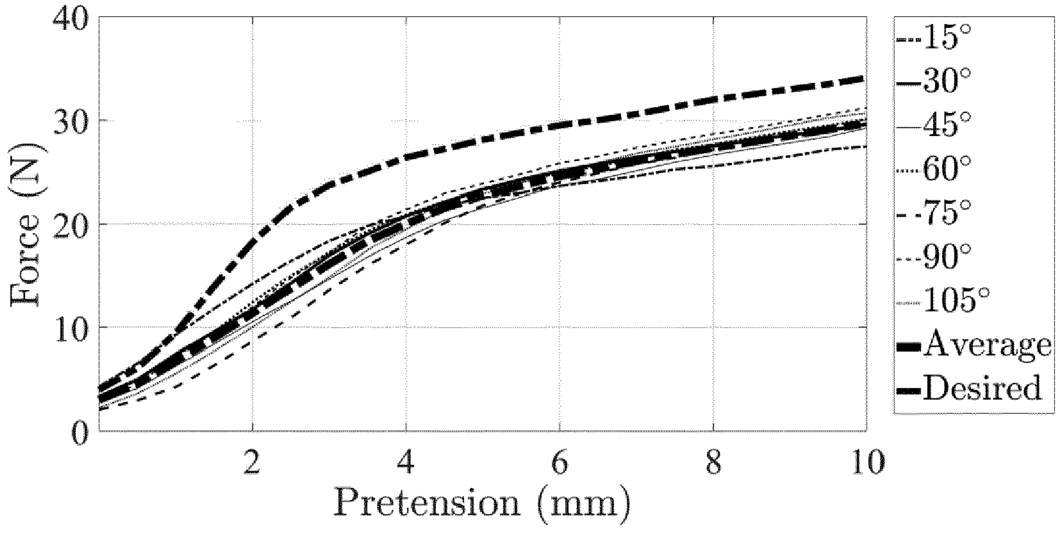

40
30
20
10
0
Force (N)
2
4
6
8
10
Pretension (mm)
15°
30°
45°
60°
75°
90°
105°
Average
Desired

Fig.7

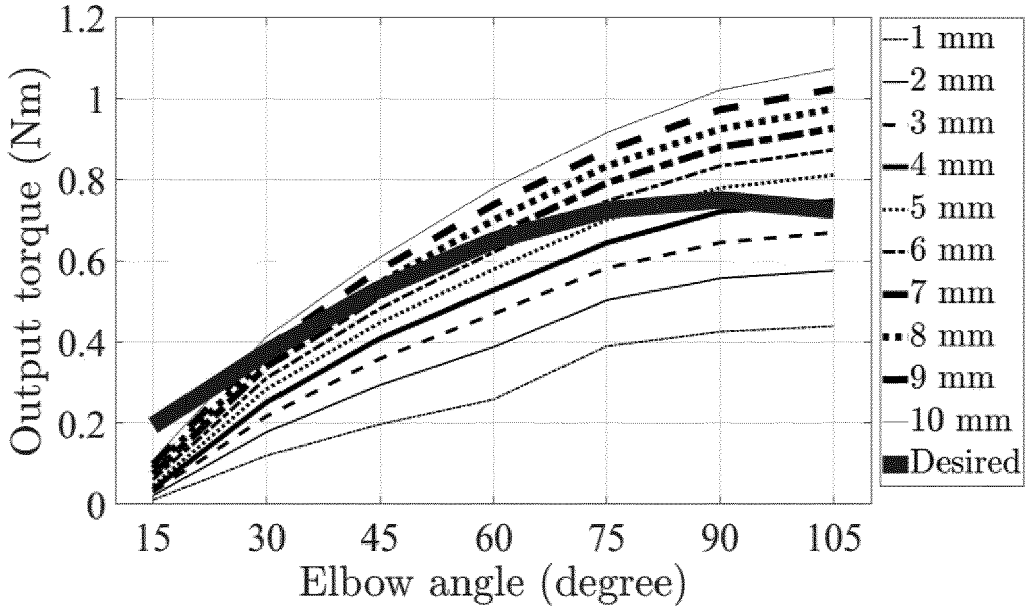

1.2
1
0.8
0.6
0.4
0.2
0
Output torque (Nm)
15
30
45
60
75
90
105
Elbow angle (degree)
1 mm
2 mm
3 mm
4 mm
5 mm
6 mm
7 mm
8 mm
9 mm
10 mm
Desired

Fig.8

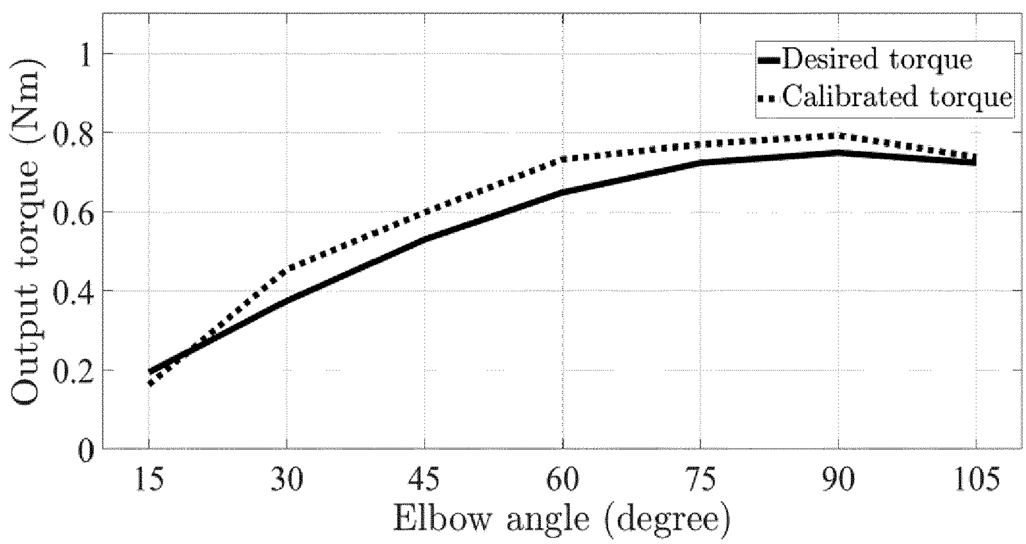
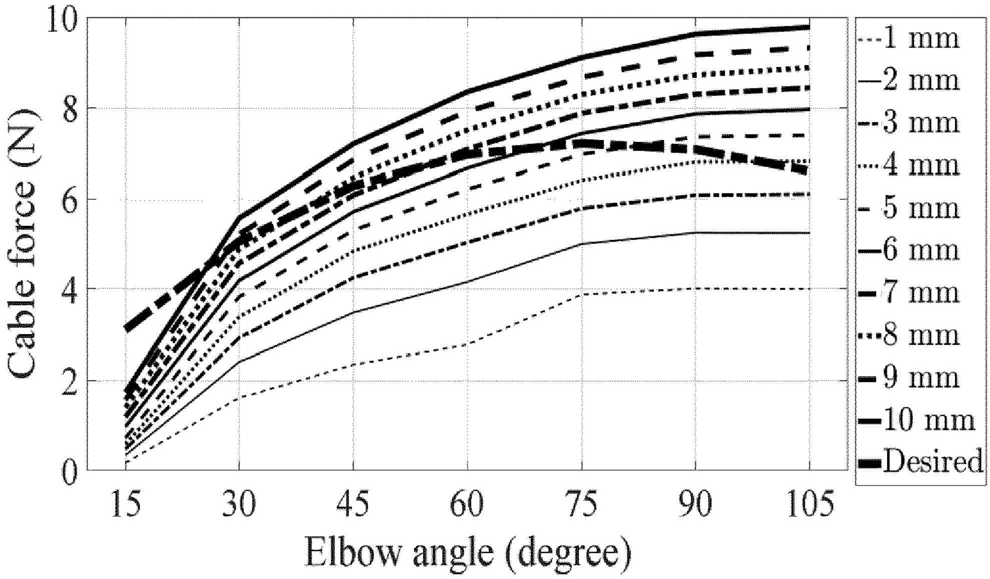
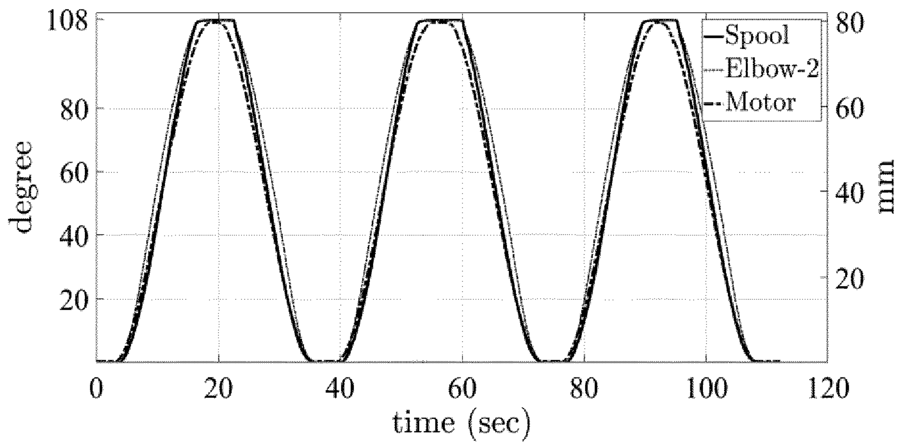

1
0.8
0.6
0.4
0.2
0
Output torque (Nm)
15
30
45
60
75
90
105
Elbow angle (degree)
Desired torque
Calibrated torque

Fig.9



10
8
6
4
2
0
Cable force (N)
15
30
45
60
75
90
105
Elbow angle (degree)
1 mm
2 mm
3 mm
4 mm
5 mm
6 mm
7 mm
8 mm
9 mm
10 mm
Desired

Fig.10



108
80
60
40
20
degree
0
20
40
60
80
100
120
time (sec)
80
60
40
20
mm
Spool
Elbow-2
Motor

Fig.11

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 22 19 4044

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	WO 2017/026943 A1 (UNIV NANYANG TECH [SG]; UNIVERSITA' DEGLI STUDI DI GENOVA [IT] ET AL.) 16 February 2017 (2017-02-16) * pages 4-9; figures 1-12 * -----	1-11	INV. A61H1/02
A	WO 2014/151584 A1 (ALTERG INC [US]) 25 September 2014 (2014-09-25) * paragraphs [0059] - [0090]; figures * -----	1-11	
A	US 2020/000670 A1 (XIONG CAIHUA [CN] ET AL) 2 January 2020 (2020-01-02) * paragraphs [0037] - [0050]; figures * -----	1-11	
A	WO 2018/165413 A1 (ABILITECH MEDICAL INC [US]) 13 September 2018 (2018-09-13) * pages 10-22; figures * -----	1-11	
A	US 2020/261298 A1 (KIM KYU JUNG [KR] ET AL) 20 August 2020 (2020-08-20) * paragraphs [0033] - [0090]; figures * -----	1-11	

TECHNICAL FIELDS SEARCHED (IPC)

A61H

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	9 January 2023	Teissier, Sara

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
....
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO. EP 22 19 4044

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report.
The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

09-01-2023

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2017026943 A1	16-02-2017	CN 107921628 A	17-04-2018
		EP 3334572 A1	20-06-2018
		SG 10201912505Y A	27-02-2020
		WO 2017026943 A1	16-02-2017
WO 2014151584 A1	25-09-2014	US 2015374573 A1	31-12-2015
		US 2019015284 A1	17-01-2019
		WO 2014151584 A1	25-09-2014
US 2020000670 A1	02-01-2020	CN 108818618 A	16-11-2018
		US 2020000670 A1	02-01-2020
WO 2018165413 A1	13-09-2018	CN 110997245 A	10-04-2020
		JP 2020509834 A	02-04-2020
		US 2020030177 A1	30-01-2020
		US 2020179213 A1	11-06-2020
		WO 2018165413 A1	13-09-2018
US 2020261298 A1	20-08-2020	CN 111571566 A	25-08-2020
		KR 20200101572 A	28-08-2020
		US 2020261298 A1	20-08-2020

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- WO 2017026943 A1 **[0008]**
- WO 2014151584 A1 **[0008]**
- US 2020000670 A1 **[0008]**
- WO 2018165413 A1 **[0008]**
- US 2020261298 A1 **[0008]**