2017 International Conference on Rehabilitation Robotics (ICORR)
QEII Centre, London, UK, July 17-20, 2017.

A passive wrist with switchable stiffness for a body-powered hydraulically actuated hand prosthesis

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***Abstract* —State of art upper limb prostheses lack several degrees of freedom (DoF) and force the individuals to compensate for them by changing the motions of their arms and body. Such movements often yield to articulation injuries, nonetheless these could be prevented by adding DoFs, for instance, an articulated passive wrist. Available stiff or compliant wrists with passive flexion/extension and/or radial/ulnar deviation are sub-optimal solutions. Indeed, stiff wrists induce the individuals wearing them to perform exaggerated compensatory movements during the reaching phase while compliant wrists proved to be unpractical while manipulating heavy objects. Here we present a wrist capable of combining the benefits of stiff and compliant wrists. It is provided with two switchable levels of passive compliance that are automatically selected. The prototype was integrated in a body-powered hydraulic hand prosthesis and actuated using the same hydraulic circuit of the hand. Detailed analysis of the parameters that affect the compliance, the critical load and the performance of the prosthesis are presented.**

I. INTRODUCTION

The development of a natural hand prosthesis as a substitute of the biological limb, after amputation, is one of the most fascinating and open challenges in rehabilitation engineering. The limits that prevent the advent of next generation prostheses, are well known and pertain to both the human machine interface [1], [2] and to the physical features of the device. Among the latter ones, the most crucial is probably the lack of compact and reliable actuators with power densities similar to the human muscles. This deficit, combined with design trade-offs pertaining to desired performance, control inputs, prehension capabilities and anthropomorphism, implies that a reduced set of movements can be fitted inside a hand prosthesis [3].

The design of currently available prosthetic wrists represents a striking example of such a simplification. With its three degrees of freedom (DoFs), the natural wrist contributes to the execution of a grasping and manipulation task, by orienting the hand in space. However, in modern upper limb prostheses, such elegance is synthetized with a single DoF; wrists are primitive, albeit useful, rotators that enable to pronate/supinate the hand [4], [5], [6].

Figure 1 The hydraulic wrist integrated with the Delft Cylinder Hand [13].

Wrists with passive flexion/extension and/or radial/ulnar deviation were also demonstrated and made commercially available [6]; these can be classified into *stiff* and *compliant* wrists. Stiff wrists enable the user to manually orientate and lock the hand in a desired and firm position [7]. Compliant wrists can also be manually locked in a certain position, but when unlocked they exhibit an elastic behavior. Hence, as their name suggests, they allow for adaptation of the prosthesis during reaching and grasping, as well as other Activities of Daily Living (ADLs), e.g. bike-riding [8].

A number of studies compared the performance of stiff versus compliant wrists, during ADLs [8]-[10]. All of them revealed improved functionality for most of the ADLs (in particular: bimanual tasks and tool manipulation) when using the compliant wrist, with the exception of those tasks which involved the manipulation of heavy objects; these tasks were better performed with a stiff wrist. These studies highlighted the limitations of both kinds of passive wrists. Stiff wrists force the users to perform exaggerated compensatory movements (which are known to cause discomfort and secondary injuries in the long run [11]), during the reaching phase. Compliant wrists proved impractical while manipulating objects, particularly heavy ones.

Based on these findings we recently developed a wrist concept capable of merging the benefits of stiff and compliant 2-DoFs wrists [12]. This was made possible by means of a mechanism that switched the compliance of the wrist joint between two fixed levels of compliance. Hence the wrist could exhibit the most appropriate level of compliance in the different phases of the grasp: i.e. compliant during the reaching phase and stiff during the holding and manipulation phases. In this work we adapted this concept, to the case of a body-powered hand prosthesis: the Delft Cylinder Hand [13]. This is a five fingered hand, with hydraulic actuation, driven by a unique master cylinder

This work was supported by the European Commission under the NEBIAS project (EU-FP7-FET-611687).

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(MC) voluntarily activated by the user (Fig. 1). When the piston of the MC is pulled, the pressure of the hydraulic circuit increases and the seven pistons connected to the digits move, in parallel, in order to close the hand. The new wrist was designed in order to use the same hydraulic circuit of the hand, i.e. avoiding the need of additional control inputs.

Although hydraulic transmissions are an efficient and reliable solution, and they have been frequently investigated to develop externally powered hand prostheses [14], [15], this is the first example of a body powered prosthetic wrist with hydraulic actuation. Detailed analysis of the physical parameters that affect the compliance, the critical load of the device and the effects of the integration of the wrist on the performance of the obtained prosthesis (hand plus wrist) are presented.

II. Rationale for the Design

As a typical grasp can be segmented into a *reaching*, a *grasping* and a *manipulation* phase, we proposed the following scenario (Fig. 2) [12]. During the *reaching* phase, the wrist is compliant so that the hand can be easily aligned to the target object by pushing the hand against constraints in the environment (e.g. a vertical wall, a horizontal shelf, etc.). Once aligned, the user voluntarily closes the hand around the object (*grasping* phase); during this phase, the wrist automatically switches to the stiff mode (Fig. 2). As soon as the object is grasped, the user can safely move and precisely manipulate the object with the rigid wrist (*manipulation* phase). Hence the transition in the wrist from *compliant mode* to *stiff mode* must be synchronous with the closure of the hand.

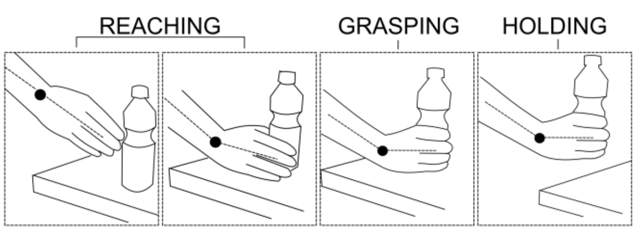

Figure 2. The typical grasp sequence.

Other requirements for the hydraulic wrist regarded both its physical structure and the integration of its actuation system with the hydraulic circuit of the Delft Cylinder Hand.

Size and weight. Body powered prostheses, such as the Cylinder Hand, present maneuverability and lightness as their distinctive features. Hence small size and reduced weight (the lowest possible) were the most important requirements for the design of the wrist.

Control input. The wrist was required to operate with the same input of the hand (i.e. same cable and hydraulic circuit) in order to keep at minimum the complexity in controlling the prosthesis. Moreover, the additional force and stroke required on the cable (by the user), due to the wrist, were expected to be as small as possible (i.e. < 10 % in force and stroke).

Range of motion. The minimum range of motion of the wrist was ±25° for the radial/ulnar deviation and to ±35° for the flexion/extension, based on our previous observations [12].

Critical load (CL). The CL was defined as the external load applied to the prosthesis, while grasping, that causes an unwanted unlocking of the wrist. As a unique hydraulic circuit served the hand and the wrist, the CL depended on the actuation force produced by the user on the cable to voluntarily close the hand. The CL was required to be always larger than the force necessary to achieve a stable thumb-index pinch grip. This requirement was aimed to avoid wrist failures during the manipulation of every objects the hand is capable to hold. In particular:

i) the $CL|F_{MAX}$, i.e., the minimum required CL corresponding to the maximum actuation force allowed on the control cable (100 N), was set to 50 N. In other words this meant that a ~5 kg object could be successfully hold by the wrist with the maximum activation force of the prosthesis.

ii) The $CL|F_{MIN}$, i.e., the minimum allowed CL corresponding to the actuation force level below which the hand can move (20 N), was set to 10 N.

III. Hydraulic-Mechanical Design

The designed wrist comprises two main components: (i) the actual wrist joint – that covers a certain workspace while exhibiting a certain compliance, and (ii) the hydraulic circuit and valves – that lock the wrist in position (i.e. switch the compliance).

A. Wrist Joint

The wrist is based on an off-the-shelf, plastic ball joint with enough excursion angle (± 35°). The ball joint links a wrist base (connected to the prosthetic socket) to a top plate (connected to the hand), thus implementing a 2 DoFs mechanism (namely flexion-extension and abduction-adduction). The third DoF of the joint (i.e. wrist rotation) is locked by a compression spring rigidly fixed between the wrist base and the top plate, coaxially with the ball joint axis (Fig. 3a). Importantly, the spring is responsible for the elastic behavior exhibited by the wrist (*compliant mode*), because when the hand is loaded, the spring bends and displaces the hand. The pre-load of the spring had to sustain the hand plus a certain weight, in correspondence to the rest position (i.e. the straight wrist); the force-displacement characteristic had to be compliant enough in order to easily adapt during the reaching phase.

Four identical hydraulic cylinders are mounted between the wrist base and the top plate, by means of encapsulated spherical joints. The cylinders are placed at the four angles of an ideal square, equidistant from the ball joint (Fig. 3a); pairs of opposite cylinders are actuated together. When hydraulically locked, the cylinders, keep the wrist in position (*stiff mode*), vanishing the effects of the spring. Contrariwise, when free to compress, a bending of the wrist produces an equal but opposite amount of stroke in two opposite cylinders.

The workspace of the top plate (and thus of the hand) is the curved surface of a spherical cap (±35° in all directions).

B. Hydraulic Circuit and Valves

Each pair of opposite cylinders is supplied by one branch of the hydraulic circuit (Fig. 4), regulated by one control valve (Fig. 3b). When the two control valves are opened the wrist exhibits 2 elastic DoFs (*compliant mode*) due to the spring. As the cylinders are symmetric with respect to the main axis, while the wrist bends the volume of fluid ejected by one compressed cylinder is equal to the volume drawn by the opposite cylinder. The friction in this circuit is negligible with respect to the reaction force of the spring. When the control valves interrupt the fluid flow in the paired cylinders the wrist locks in position (*stiff mode*).

The two control valves were designed in a single body (Fig. 3b top view) both to be supplied by a single inlet (I in Fig. 3b) connected to the main actuation system of the prosthetic hand (Fig. 4). Two outlets in each valve (O_1 and O_2 in Fig. 3b) regulate the flux of fluid for each pair of opposite cylinders. The extremity of the piston is a disk embedding a rubber seal. When the valve is actuated (pressure applied by the fluid at the inlet) the piston slides down forcing the rubber seal against the hole at the bottom of the valve, thus obstructing the fluid flux between two opposite cylinders. When the piston is no longer actuated (i.e. there is no pressure coming from the actuation system) a compression spring pushes the piston in the rest position, thus re-opening the valve.

1) Hand-Wrist Integration and Extra-Stroke

The wrist valves and the hydraulic circuit of the hand were integrated by means of a *T* hydraulic connection. In this way when the MC actuated the (seven) cylinders of the hand it would also actuate the wrist, in parallel, thus synchronizing the stiffness-switch with the grasp (Fig. 4). However, adding the wrist to the hand implied an additional piping and additional volume of fluid to be moved; in other words, increased pressure drop and stroke of the MC.

The increase in the pressure drop could be deemed negligible due to the short length of the piping, its uniformity and the very low velocity of the fluid during use. Instead, the increase of the MC stroke (ΔS_{MC}) associated to the cubic capacity of the two valves (V_V), had to be taken into account. Indeed, the V_V can be ruled as:

$$V_V = S_V {d_I}^2 \frac{\pi}{4} \tag{1}$$

where S_V is the stroke of the pistons in the valves and d_I is the diameter of the valve (Fig. 5). The ΔS_{MC} can be written as:

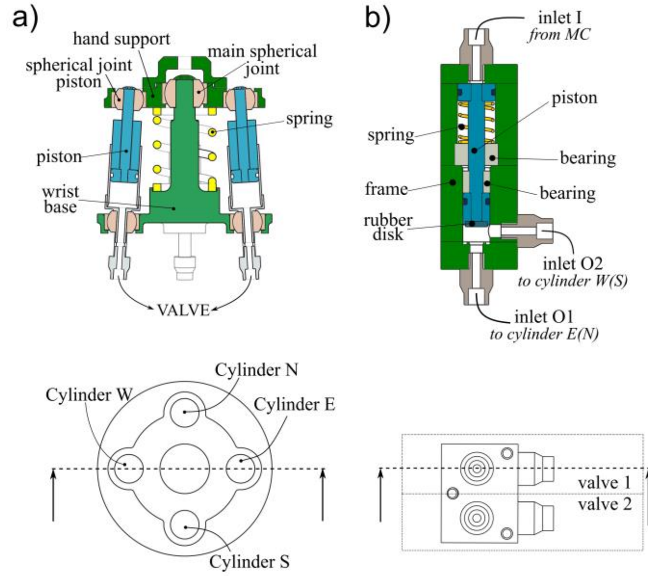

Figure 3. Cross section of the wrist (a) and the valve (b).

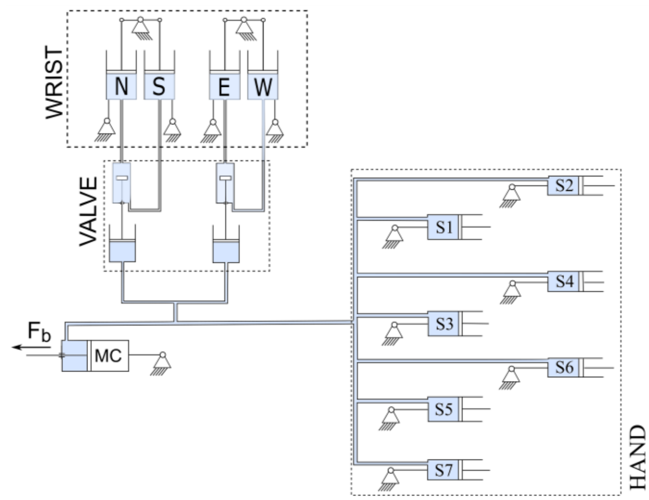

Figure 4. Hydraulic scheme of the actuation of the wrist integrated with the Delft Cylinder Hand.

$$\Delta s_{MC} = \frac{2V_V}{{d_{MC}}^2\frac{\pi}{4}} = \frac{2S_V d_I}{d_{MC}} \tag{2}$$

with d_{MC} the diameter of the MC. As the user is capable of delivering a limited input movement, the ΔS_{MC} had to be minimized (in order to allow him/her to fully close the hand). To this aim the valve was designed keeping d_I as small as possible, assuming the size of the pre-existent MC as fixed.

2) Critical Load – Static Analysis

The CL is the external load (or interaction force) applied to the prosthesis, while grasping, that causes the undesired reopening of the wrist valves, hence the unlocking of the wrist. The equation that rules the CL with the force produced by the user on the MC (F_{MC}) was pivotal for designing a wrist valve properly integrated with the pre-existing circuit.

The force generated by the user on the MC, F_{MC}, is hydraulically transmitted to the pistons of the valves, as F_I, where it tends to close the valve. When the valves are closed, and the hand is externally loaded (F_{EXT}), the pressure in the wrist circuit(s) increases (Fig. 5). This increase produces a force on the piston of the valve, F_O, which is opposite to F_I and tends to reopen the valve. When $F_O > F_I$ the wrist becomes compliant.

Considering the structure of the valve with one outlet coaxial (O_1 in Fig. 5) and the other orthogonal (O_2 in Fig. 5) with the axis of the piston, the most relevant condition is when the pressure is applied from the coaxial outlet[1]. This may occur when F_{EXT} loads the cylinder connected to outlet O_1 (e.g. cylinder E in Fig. 5). In this case, indeed, F_O directly counteracts the input force, F_I, through the piston:

$$F_O = (F_{EXT} - F_S)\frac{l_H}{l_W}\frac{{d_O}^2}{{d_W}^2} \tag{3}$$

where F_{EXT} is taken tangential to the hand and F_S is the resulting reaction force acting in the palm of the hand developed by the spring. l_W is the distance between the center of rotation of the wrist and the axis of the cylinder; l_H is the moment arm of F_{EXT} (Fig. 5). d_O and d_W are the section diameters of the outlet O_1 and of the wrist cylinder, respectively. F_I can be written as:

$$F_I = F_{MC}\frac{{d_I}^2}{{d_{MC}}^2} - F_{SV} \tag{4}$$

where d_{MC} is the diameter of the MC, F_{SV} is the reaction force of the spring in the valve. The valve unlocking condition is:

$$F_O > F_I \;\Rightarrow\; F_{EXT} > F_{MC}\frac{({d_I}^2 l_W {d_W}^2)}{({d_{MC}}^2 l_H {d_O}^2)} \tag{5}$$

It was calculated for the most conservative case (i.e. wrist in axial position), thus F_S (null in that case) and F_{SV} (always orders of magnitudes lower compared to the other applied forces) are left out.

From equation (5) we can extract R which describes the ratio between the CL and the F_{MC}, i.e. the proportion between the force voluntarily applied by the user and the CL.

$$R = \frac{({d_I}^2 l_W {d_W}^2)}{({d_{MC}}^2 l_H {d_O}^2)} \tag{6}$$

$$CL = F_{MC}R \tag{7}$$

Notably, four out of six parameters in R (l_W, l_H, A_W and A_{MC}) were already fixed/constrained by the geometry of the hand and of the wrist. Instead, d_I and d_O could be chosen by design.

A R equal to 0.5 was chosen for designing and manufacturing the valve. This yielded to a ratio of 3:1 between d_I and d_O ($d_I = 3\ d_O$). As d_V required to be as small as possible (cf. previous paragraph) d_O also had to be minimized. Coherently with the requirements of the pre-existing hydraulic system we chose d_O equal to 2 mm. This choice yielded to an increase of the input stroke equal to 3.6% the original stroke (ΔS_{MC} = 1.35 mm – experimentally assessed).

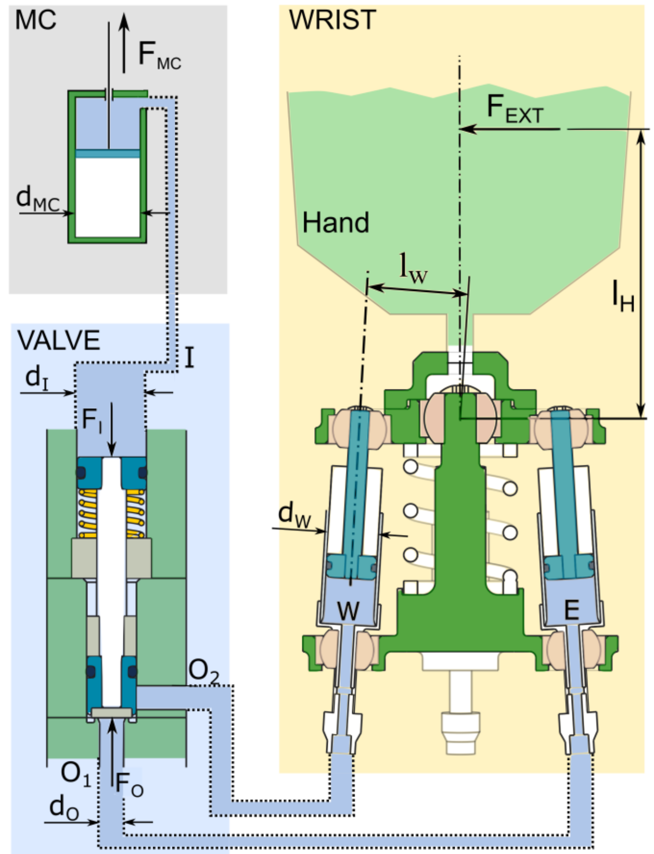

Figure 5. Scheme of the hydraulic circuit and forces involved during wrist use.

IV. Manufacturing

The wrist was manufactured and integrated with the Delft cylinder hand (Fig. 1). The components subjected to corrosion, such as cylinders, pistons and valves were manufactured in stainless steel. Less critical components were manufactured in aluminum. The requirements regarding the: (i) size and weight, (ii) control input, (iii) range of motion, and (iv) critical load were met. The developed prototype proved comparable in terms of weight and dimensions with clinically available body-powered prostheses [16]. In particular, the maximum diameter and length of the wrist were 45 mm and 55 mm, respectively. The first prototype weighs ~130 g (wrist weight = 60 g, valve weight = 70 g).

V. Experimental Measurements

The hydraulic wrist integrated with the Delft Cylinder Hand was tested in order to experimentally assess: i) the stiffness of the wrist in compliant mode, ii) the CL of the wrist, and iii) the force-displacement characteristic exhibited

[1] When the pressure is applied from outlet O_2 the force is applied to a smaller surface.

by the MC in order to operate the hand. An instrumented test bench was used to carry out all the measurements. It included a manually adjustable slide equipped with a load cell (Zemic: FLB3G-C3-50 kg-6B) and a displacement sensor (Schaevitz: LCIT 2000). In the third measurement, a graspable (thickness of 10 mm) custom made load cell was also used.

A. *Stiffness*

The base of the wrist was constrained horizontally to a bench whereas the top plate was connected to an appendix (length 100 mm) that stood out vertically and mimicked the hand. The wrist was set in *compliant mode* and loaded through the tip of the appendix by means of a steel cable connected to the instrumented slide. The wrist was progressively loaded until it reached the maximum angular displacement (35°). Four repetitions were performed. The force and position recorded by the instrumented slide were used to compute the reaction torque and the angular displacement of the wrist.

B. *Critical Load*

The wrist was set in *stiff mode* at different pre-defined values of F_{MC} on the MC: from 10 N to 100 N with steps of 10 N. For each F_{MC} condition the wrist was then loaded, as in the previous measurement, until the CL condition occurred. The latter was identified as the instant when the wrist started to move. This test was repeated 80 times: for each F_{MC} the wrist was loaded in eight positions around its axis, in steps of 45°.

C. *Force-Displacement Characteristic of the MC*

The MC was fixed to the instrumented slide in such a way that the force and the displacement of the piston could be recorded. The hand was operated through the MC in order to open/close it without actually grasping, in a quasi-static conditions. The force-displacement characteristic of the piston was experimentally assessed with and without the wrist.

VI. RESULTS

A. *Stiffness*

The spring produced a reaction torque (solid line Fig. 6a) compatible with the requirement of balancing the weight of the hand (0.14 Nm, dashed line Fig. 6a) without sensible displacement. The reaction torque (0.18 ± 0.02 Nm; mean ± std. deviation) measured in the axial position (i.e. angular displacement = 0°), due to the preloading of the spring, was sufficient to maintain the hand aligned with the forearm when the wrist was in compliant mode. The maximum reaction torque (1.2 ± 0.04 Nm) reached at maximum bending of the wrist was deemed sufficiently low. This should allow the user to exploit the entire range of motion of the compliant wrist without experiencing excessive interaction forces.

B. *Critical Load*

As expected the CL proved different based on the direction of the external load. In fact, the CL was larger when the cylinders S and W were loaded (wrist loaded at 0° ÷ 90°, max CL = 300 N at 45°, Fig. 6b) compared to cylinders N and E (wrist loaded at 180° - 270°, min CL = 49 N at 180°). In the worst case, the CL proved proportional to F_{MC} with a ratio of 0.49 (Fig. 6b). This was compatible with the design requirement of allowing the user to sustain an external load larger than the thumb-index pinch force. Furthermore, the wrist could sustain a weight of at least 4.9 kg with a 100 N activation force (F_{MC}) and a 0.9 kg weight with the minimum activation force needed to close the hand.

C. *Force-Displacement Characteristic of the MC*

The activation force required to close the hand was the same (as expected) with and without the wrist, equal to 46±1 N. The insertion of the wrist did not significantly change the force-displacement characteristic of the MC (presented in our previous work [13]). In quasi-static conditions the wrist yielded to a shift (0,5% of the MC displacement of the sole hand) in the characteristic (Fig. 6c), due to the extra stroke. This result suggests that a user would not experience particular differences while operating the control cable.

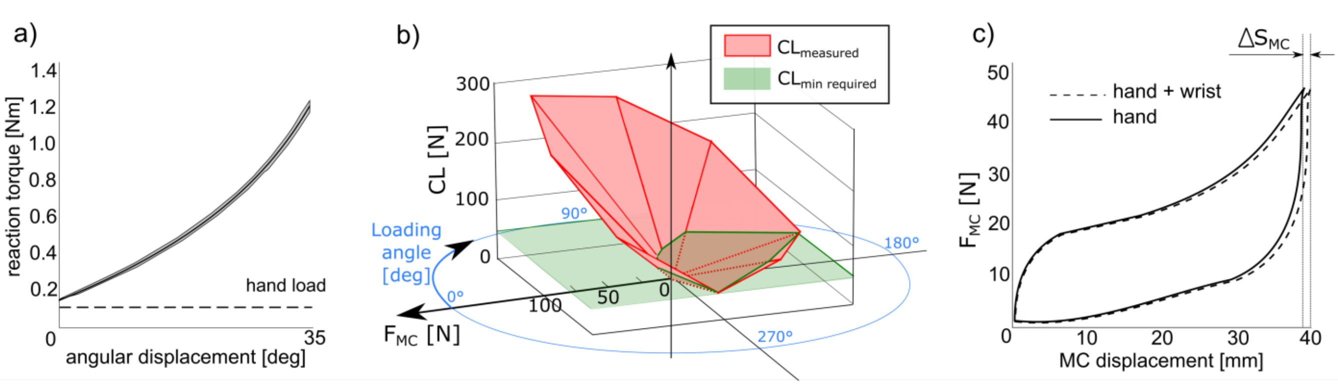

Figure 6. Experimental assessment. a) Stiffness of the wrist (reaction force versus angular displacement) mean (solid line), ± std. deviation (grey area). The superimposed dashed line depicts the hand load (due to the weight). b) Measured Critical Load (red), minimum CL required at maximum F_{MC} (green area). c) Force-Displacement Characteristic of the Master Cylinder.

VII. CONCLUSION

In this work, the design and the experimental assessment of a compliant wrist with switchable stiffness, for a body-powered prosthesis, were presented. In particular, we transferred the concept shown in our previous design, based on electrical motors and myoelectric prostheses, to the domain of hydraulic systems and body-powered devices. The interesting aspect in this transfer was that there was no need to synchronize the switching of the wrist with the grasping phase as this was automatically implemented by the hydraulic circuit.

The choice of exploiting a spherical joint in order to enable the flexion/extension and radial/ulnar deviation movements was deemed as the most effective for limiting the dimensions in both the radial and axial directions. This solution, already demonstrated in both research [17] and commercial/clinical [18] domains, was preferred over other solutions like universal joints and differential mechanism, already investigated by the authors [12].

The spring, the spherical joints and the piping connections were off-the-shelf components. Noteworthy, the choice of the spring affected the dimensions of the device, especially its diameter. Hence, this work invites further developments aimed to customize these parts in order to optimize weight and dimensions.

The valve comprised two pistons each regulating the flux of a pair of opposite cylinders. For design reasons, the current valve architecture is asymmetric resulting in a different CL depending on the load (F_{EXT}) direction. However, the current design proved to fulfill the requirements for every load condition. Additionally, such design was preferred to single-piston symmetric designs (which are usually more compact solutions), due to the easier manufacturing process involved. Nonetheless, a different choice in the materials and architecture used could reduce the weight and dimension of the valve, in future developments.

The seals proved to be crucial components for the design. The seals of the pistons were the same as those used in the cylinders of the hand. These were optimized in our previous work [13] in order to minimize wear and leak of fluid that are frequent failure causes for this kind of solutions. Instead some of the seals used in the valve, albeit reasonably effective, could be further investigated. In particular, the valve prototype used vulcanized rubber disks on the head of the pistons. Different materials like urethane or silicone rubber, and different shapes of both the seal and the counteracting surface could be investigated in order to improve the CL and manage the wear effects.

ACKNOWLEDGMENT

Authors would like to thank Jan Frankenhuyzen for significant advices in the prototype design.

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