Improvements on the design of the *S-Finger* prosthetic digit

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***Abstract*— Partial hand amputations are the most common amputations worldwide, yet their prostheses, especially battery-powered ones, are only slowly progressing. As a result, only few clinical solutions are available. We developed a prototype of a powered prosthetic finger (dubbed *S-Finger*) that is equipped with a mechanical transmission alternative to the already available solutions which comprises of a miniaturized non-back drivable mechanism. Here we present the design criteria and the details of an optimized design that comprises of a non-backdrivable mechanism and a miniaturized Oldham joint.**

I. Introduction

PARTIAL hand amputations represent the most common amputation level regarding the upper extremities, covering 90% of them [1]. However, the progress of partial hand prostheses has been limited compared to other ones (e.g. leg or articulated full hand prostheses) [2]. Yet, the design progress is also influenced by the difficulty of substituting the anatomical muscle drive and sensory system with a motor and artificial sensors as in a size of a digit. In a previous work [3] we presented the architecture, alternative to state of the art solutions, which exploits a high efficiency, non-back drivable mechanical transmission based on a face-gear pair and a miniaturized clutch. As a result, the digit exhibits speed comparable to the commercial available prostheses and it is able to sustain large passive loads. This architecture took inspiration from the synergetic prehension approach proposed by Childress [4] for a whole hand amputation, which is the reason why it was dubbed *S-Finger*. The proposed design proved to be compact and rugged enough to undergo a clinical viability test with two partial hand amputees, fitted with custom three-fingered research-prostheses. However, during this test, we realized that a further revision of the design was required in order to improve the performance and reliability of the digit enabling its exploitation for daily use. The present abstract reports the mechanical design of the optimized transmission of the *S-Finger*.

II. Materials and Methods

In order to optimize the transmission, a revision of the first prototype was performed resulting in the task to re-design the non-backdrivable mechanism (NBDM) and to include a miniaturized Oldham coupling joint able to provide for misalignment between the motor and the driven shafts that may occurs during the assembly.

A. Optimized non-backdrivable mechanism

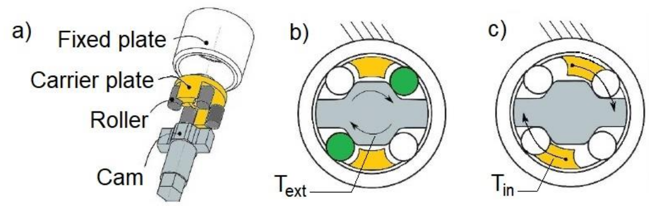

Fig. 1. Overview of the previous design of the NBDM of the *S-Finger*: A) exploded view. B) NBDM in its locked condition, cross section. The cam is forced from the output shaft (cam, gray) by an external torque T_{ext} resulting in wedged rollers (green) preventing the rotation of the cam. C) NBDM in its unlocked condition, cross section. When the motor is driven, the torque T_{in} is transferred to the carrier plate (yellow) unlocking the rollers. (Adapted from [3]).

The NBDM (Fig. 1) is an essential, but a rather complex structure based on numerous elements requiring a precise manufacturing process. The non-backdrivability is based on friction occurring between the rollers, the fixed plate and the (output) cam [5]. Hence, when an output torque T_{ext} is applied to the cam, the rollers are wedged between the fixed ring and the cam. Yet, when an input torque T_{in} is applied by the motor to the carrier plate, the rollers are moved out of their wedged condition, enabling for the transmission of the power from the carrier plate to the output cam. The NBDM was revised regarding its contact angle according to the NBDM guidelines reported in [5]. The most critical parameters of a non-backdrivable roller clutch mechanism are the coefficient of static friction μ_s between the interfaces, and the *contact angle* α. This is defined as the angle existing between the line joining the contact points at the roller/cam and the roller/fixed ring interfaces and a line perpendicular to the cam surface. The locking condition is ensured when the tangent of the contact angle is smaller than the coefficient of friction at the contact. On the other hand, the contact angle α should be chosen in order to minimise the effort required to unlock the rollers (that is obtained for wide α).

B. Miniaturized Oldham joint

With respect to the original design proposed in [3], a miniaturized joint was interposed between the motor shaft and the input of the NBDM to provide for misalignment between two shafts that results from the assembly and that may reduce the life of the motor gearhead. This miniaturized joint was based on an Oldham coupling (Fig. 2) and comprises three

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elements, which have sliding contacts to each other. Therefore, the mid element (Oldham connector) is responsible to keep the contact between the input and output element when a misalignment occurs based on over-constraints/errors of the assembly allowing for a continuous torque transfer.

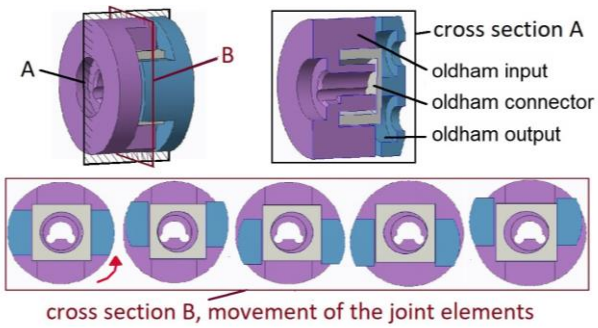

Fig. 2. Design of the miniaturized Oldham coupling joint. Top left: assembled Oldham coupling. Top right: cross section 'A' of the assembled joint. Bottom: cross section 'B' of the assembled joint showing the sliding movement of the single parts with respect to each other.

III. Results

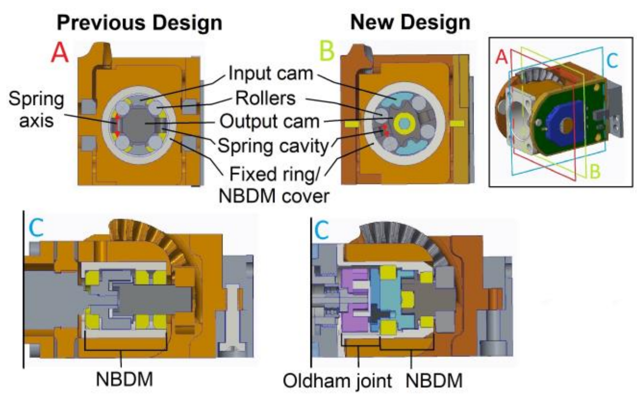

Fig. 3. Comparison between the previous and the new design of the mechanical transmission of the *S-Finger*. Top row: horizontal cross section (A, B) of the finger at the NBDM level. Bottom row: sagittal cross section (C) of the NBDM. The new design includes a miniaturized version of an Oldham coupling joint.

The contact angle of the NBDM was chosen to be 6.72° when considering a friction coefficient of 0.14 (experimental value found for a steel-steel contact). Subsequently, the required (theoretical) unlocking torque T_u, which moves the rollers in their unlocked condition and drives therefore the system, is reduced by a factor of about 2.2 respect to the first prototype [5]. Furthermore, the shapes of the input and output shafts were modified (Fig. 3). In the new design, when a torque is applied to the input, it is able to drag the output. Yet, the input shaft cannot be driven by the output cam since it will reach its locked condition first, hindering the contact between the output and input cam. Moreover, the alignment between the springs and the rollers is improved (Fig. 3) meaning that the springs transfer their forces closer to the center axes of the rollers warranting that the rollers are pushed against the fixed ring supporting the locked condition. Instead previously, the forces were applied towards the roller edges counteracting the locked condition by pushing the rollers away from the fixed ring.

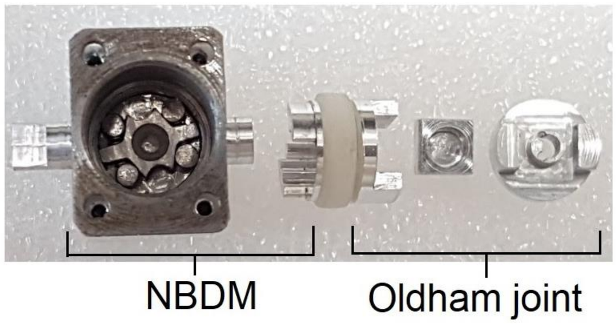

Fig. 4. Manufactured prototype of the new transmission (NBDM and miniaturized Oldham joint) for the revised version of the *S-Finger* [3].

The elements of the manufactured prototype are shown in Fig. 4. In order to embed the Oldham coupling joint in the *S-Finger* without increasing the original size of the transmission, the axial length of the NBDM was reduced from 11.8 mm to 8.2 mm. The new transmission weighs 9 g, it is 15.5 mm long and has rectangular section whose sides are 16 mm and 12 mm.

IV. Discussion and Conclusion

The NBDM of the *S-Finger* was designed with a reduced size in order to allow for the integration of a miniaturized Oldham joint, keeping the original size of the finger. The Oldham coupling is mandatory to provide for a certain compliance to the assembly lowering the risk of damaging the motor due to assembly constraints or misalignments. Besides, the unlocking torque T_u of the new NBDM design was reduced by a factor 2.2, with the result that the energy loss due to the unlocking phase was reduced. Further works will be focused on the assessment of the transmission developed.

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