Multifilament Pneumatic Artificial Muscles to Mimic the Human Neck

Arnau Garriga-Casanovas[1,3], Ahmad 'Athif Mohd Faudzi[1,2], Tatsuhiro Hiramitsu[1], Ferdinando Rodriguez y Baena[3], Koichi Suzumori[1]

***Abstract*— Pneumatic Artificial Muscles (PAMs) are actuators that resemble human muscles, and offer an attractive performance in various aspects including robustness, simplicity, high specific power and high force for a given volume. These characteristics render them good candidates for use in humanoid robots. The use of traditional PAMs to closely mimic human structures, however, is difficult due to their relatively large size and relatively fixed designs. The recent development of multifilament PAMs enables the realization of humanoid robots that more closely mimic the human anatomy. In this paper, the application of multifilament PAMs to mimic the human neck is presented. First, the main structures of the human neck anatomy in terms of bones, ligaments and muscles are identified and detailed. The design to mimic each of these structures is subsequently described, together with the most relevant parts of the manufacturing process. The integrated neck is then presented, and the method to actuate it is outlined. The results of motion of the artificial neck when actuating different groups of muscles that mimic those in the human anatomy are reported, confirming a motion that is equivalent to that of the human neck. The results also indicate a range of motion of the robot neck somewhat lower than that of its human counterpart, and the reasons for this are discussed. Finally, future directions for improved motion range, stability, durability and efficiency are outlined.**

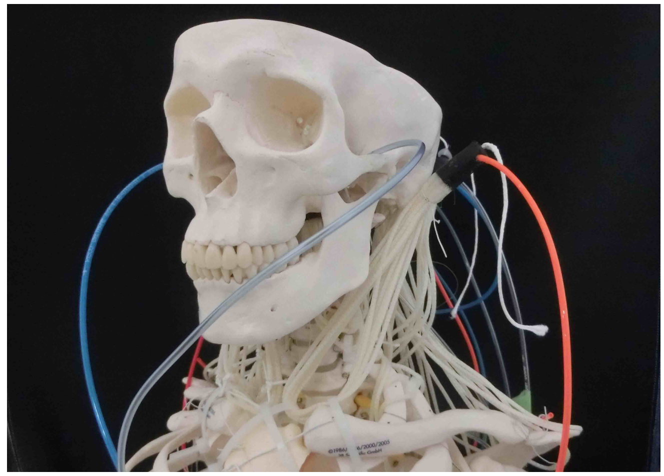

Fig. 1. General image of the integrated artificial neck.

I. Introduction

The design of the human body presents a high performance in many aspects, and is the result of millennia of evolution. Mimicking such design could therefore lead to humanoid robots with a performance that is advantageous in many applications, particularly in scenarios where the robot must interact with man-made environments that have been designed to be convenient for humans. A variety of humanoid robots inspired by the human anatomy have been proposed, including complete humanoid body designs [1], [2], or humanoid parts of the body such as the upper torso [3], [4]. The majority of these rely on traditional mechanisms and actuators, such as motors and tendons.

Traditional mechanisms and actuators make it difficult to mimic closely the human anatomy. Imitating the human anatomy requires mimicking bones, ligaments, and muscles, which involves the use of soft structures, complex muscles with varied designs, and a high number of articulations that move relying on the compliance of tissue and muscles. Instead, traditional mechanisms typically consist of components with relatively high stiffness and weight, which are articulated at a limited number of joints. In addition, and most prominently, traditional actuators tend to be relatively heavy, stiff and with predetermined designs that cannot mimic the complex structures of human muscles. Thus, the development of humanoid robots capable of human-like motions using traditional technologies is complicated, particularly due to the limitations of the actuators.

Soft robotics is an emerging field of technologies that rely on soft materials similar to those found in nature, which have the potential to mimic closely biological designs [5]. A relevant facet of soft robotics involves Pneumatic Artificial Muscles (PAMs), which consist of an elongated structure with axial symmetry and a longitudinal chamber that can be pressurized to produce radial expansion and thus longitudinal contraction of the muscle [6], [7]. PAMs offer the potential to mimic human muscles, and traditional PAMs have been used in robotic arms [8], [9], a torso [10], legs [11], [12], and infant robots [13]. However, some of the characteristics of these robots are still distant from the human anatomy, and their motion presents some differences with respect to that of the human body. This is in great part due to the fact that the design of typical PAMs is still far from that of biological muscles, and cannot reproduce some of the complex structures found in the human anatomy.

Multifilament PAMs were recently proposed [14], [15], and consist of a set of thin PAM fibers arranged in a bundle structure similar to that of human muscles. They offer various advantages including high design flexibility,

1 Department of Mechanical Engineering, Tokyo Institute of Technology 2-12-1, Ookayama, Meguro-ku, Tokyo 152-8552, Japan.

2 Center of Artificial Intelligence and Robotics (CAIRO), Universiti Teknologi Malaysia, 81310 UTM Johor Bahru, Malaysia.

3 Mechatronics in Medicine Laboratory, Department of Mechanical Engineering, Imperial College London, UK.

Corresponding author: A.A.M. Faudzi (email: athif@fke.utm.my).

low cost, light weight, miniature size, compliance, and low initial volume, which translates in a good performance even when the maximum volume available is small. In this regard, multifilament PAMs can be applied for the development of humanoid robots that closely mimic the biological design and thus provide similar motion, with a recent example reported in [15], where a human leg is mimicked.

An interesting structure to mimic is the human neck [16] and, to the best of the authors' knowledge, it has not been mimicked before. An artificial neck is necessary in a humanoid robot to provide control of the head orientation in order to direct the sensors in the head towards the desired location while the body is constrained, compensate for orientation deviations when the body moves, and provide stability during locomotion. In addition, the development of an artificial neck also serves to illustrate that human-like characteristics and motion can be achieved by imitating the human anatomy and actuation mechanism, and thus hypotheses related to human motion can be tested. Finally, the development of an artificial neck can serve for the general advancement of humanoid robots by mimicking a complex structure, and to showcase the capabilities offered by multifilament PAMs when imitating complex designs that typically arise in the process of mimicking nature.

In this paper, the development of a robotic neck that mimics the human neck, using multifilament PAMs, is reported. The artificial neck presented here mimics the structure of bones, ligaments and muscles of the human neck in order to attain a motion that is equivalent to that of the human neck. It should be noted that the human neck comprises a significant number of biological structures, resulting in a highly complex system. In this work, the focus is on mimicking the dominant structures of the human neck according to medical literature so that the resulting motion of the artificial neck is equivalent to the human one. In this regard, the main elements of human anatomy in terms of bones, ligaments, and muscles are first identified, and these are subsequently mimicked using artificial structures.

The main enabler for this work are the multifilament PAMs. These provide the design flexibility, muscle architecture, compliance, small size, and force necessary to mimic the complex structure of the muscles in the human neck. Multifilament PAMs, combined with soft materials to mimic ligaments and lightweight materials to imitate bones, allow for the development of an artificial neck with characteristics similar to those of its human counterpart.

The artificial neck presented in this paper is capable of a motion similar to that of the human neck, although the range of motion is somewhat reduced. This motion has not been reported before in the literature, and is possible thanks to the new, soft structures used in this work, which resemble biological structures. While the motion range of the artificial neck presented here is lower than that of its human counterpart, it is the authors' hope that this work will serve as a first step towards an advanced artificial neck and, more generally, towards the realization of humanoid robots.

The paper is organized as follows. The main structures of the human neck in terms of bones, ligaments and muscles, are introduced in section II. The methods to mimic these structures, with details about the manufacturing process, and the resulting integrated neck, are also described in section II. The results of motion of the artificial neck are presented in section III. The performance of the current neck design is discussed in section IV, where possibilities for future improvement are also outlined. Finally, the conclusion of the paper is presented in section V.

Structure group	Elements	Involvement in motion
Cervical vertebrae	Atlas	All
	Axis	
	C3 – C7	
Ligaments of the cervical spine	Nuchal ligament	All
	Anterior longitudinal ligament	
	Posterior longitudinal ligament	
	(Tectorial membrane)	
Ligaments of the atlas and axis	Alar ligaments	
	Cruciform ligament	
	(Transverse ligament of the atlas	
	Superior band	
	Inferior band)	
Ligaments connecting the vertebral arches	Ligamentum flavum	
	Atlanto-occipital ligament	
	Atlanto-axial ligament	
Suboccipital muscles	Rectus capitis minor	Rotation
	Rectus capitis major	
	Obliquus capitis	
Anterior neck muscles	Longus capitis	Forward flexion
	Longus cervicis	
	Scalene muscles	
Posterior neck muscles	Semispinalis	Extension
	Splenius	
	Trapezius	
	Levator scapulae	Lateral flexion
	Sternocleidomastoid	

Fig. 2. Table with the main structures of the human neck in terms of bones, ligaments, and muscles mimicked in this work. The ligaments and muscles are classified in groups following [16]. The muscles involved in each type of motion are also indicated with arrows, although it should be noted that rotation and lateral flexion involve the activation of muscles at only one side of the neck, which is not detailed for brevity.

II. Method

The human neck serves for support and movement of the head [16]. The main types of motion provided by the human neck are rotation, lateral flexion, and frontal flexion and extension. The artificial neck is developed here with the aim of reproducing all these motions, as well as supporting the head.

Mimicking the human neck requires mimicking the structures of bones, ligaments and muscles. In this work, the objective is to attain an artificial neck with characteristics similar to the human neck and that provides an equivalent motion. Thus, the main anatomic structures of the human neck were first identified, as summarized in Figure 2, and subsequently mimicked accordingly. The artificial neck presented in this paper was developed to scale, using, as reference, a human adult with a height of 160 cm.

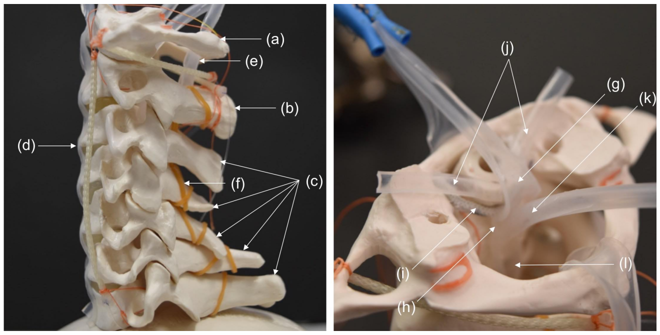

Fig. 3. Bones and ligaments of the artificial neck. The labelled bones correspond to (a) atlas, (b) axis, (c) cervical vertebrae C3-C7. The labelled ligaments correspond to (d) anterior longitudinal ligament, (e) ligamentum flavum, (f) atlanto-axial ligament, (g) superior band, (h) inferior band, (i) transverse ligament of the atlas, (j) alar ligaments, (k) tectorial membrane, and (l) posterior longitudinal ligament.

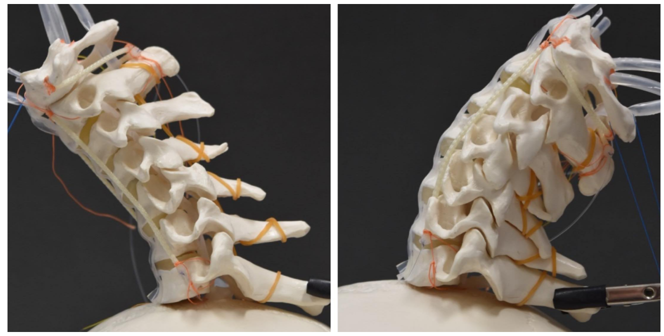

Fig. 4. Bending of the artificial neck structure in forward flexion and extension, displaying a bending mode equivalent to that of the human neck.

The main anatomic features of bones, ligaments and muscles are described in subsections II-A, II-B, II-C, together with the method to mimic them. Specific details about the manufacturing process are also included in these subsections. The integrated neck is introduced in subsection II-D. The method to actuate the neck is described in subsection II-E.

A. *Bones*

The human neck is composed of seven cervical vertebrae, which connect the base of the head to the top thoracic vertebra. The arrangement of these vertebrae together with anatomic details can be found, for example, in [17].

Intervertebral discs exist between adjacent vertebrae C3-C7 in order to protect the vertebrae and provide some joint motion. In particular, the intervertebral joints provide a certain degree of forward flexion and extension, as well as some limited lateral flexion and rotation. The result of these joints is an approximate motion range of 100° in forward flexion and extension, 35° in lateral flexion towards each side, and approximately 70° in rotation towards each side.

The joints between atlas and axis, and between head and atlas, do not have intervertebral discs, and instead rely on synovial joints. The articulation between atlas and axis leads to a rotation around the odonthoid process of the axis, leading to rotation of the head. The articulation between head and atlas provides two degrees of freedom corresponding to forward flexion and extension of the head, and lateral flexion. These articulations provide an approximate motion range of 20-30° in forward flexion and extension, 8° in lateral flexion, and 12° in rotation. The combination of the motion from these joints together with that of the intervertebral discs restricts the human neck to an approximate total motion range of 130° in forward flexion and extension, 45° in lateral flexion towards each side, and 80-90° in rotation towards each side.

In this work, the bones were mimicked using a readily available skeleton from 3B Scientific (Hamburg, Germany), with part number A15. The intervertebral discs were also imitated using those from the skeleton. Surface smoothing using sandpaper was manually applied in order to ensure a smooth articulation at the regions of contact between bones, particularly at the atlanto-occipital joint. The hyoid bone was removed, since it is not relevant to the biomechanics of the neck.

The resulting artificial bone structure can be seen in Figures 3 and 4. All bones correctly fitted into the assembly, and the articular surfaces provided a degree of articulation similar to that of the human neck.

B. *Ligaments*

The ligaments of the human neck are passive structures that maintain the bones and articulations in their correct configuration. In addition, the ligaments prevent excessive motion at the articulations.

The main ligaments of the human neck can be organized in three groups following [16], as summarized in the table in Figure 2. The first group, corresponding to the ligaments of the cervical spine, includes the nuchal ligament, the anterior longitudinal ligament, and the posterior longitudinal ligament, which is renamed tectorial membrane in its highest part, beyond the atlas. The second group, corresponding to the ligaments of the atlas and axis, includes the alar ligaments, and the cruciform ligament, which in turn is composed of the transverse ligament of the atlas, the superior band and the inferior band. The third group, corresponding to the ligaments connecting the vertebral arches, includes the ligamentum flavum, the atlanto-occipital ligament and the atlanto-axial ligament.

These ligaments were imitated by using hyperelastic materials, both silicone and rubber bands, and by reproducing the ligament geometry in order to attain a similar stiffness to that of the human equivalents, and thus enable an equivalent motion at the joints. It should be noted that the artificial joints in this work, and especially the joints involving the atlas, are not exactly equivalent to the human joints, predominantly due to higher friction between moving parts. In addition, the exact stiffness of the ligaments of the human neck *in vivo* can be difficult to determine with precision. In this regard, priority was given to obtaining a motion equivalent to that of the human neck, adapting the stiffness of the ligaments where required to compensate for practical imperfections.

The ligaments assembled into the artificial neck are shown in Figure 3, with corresponding labels. The ligamentum

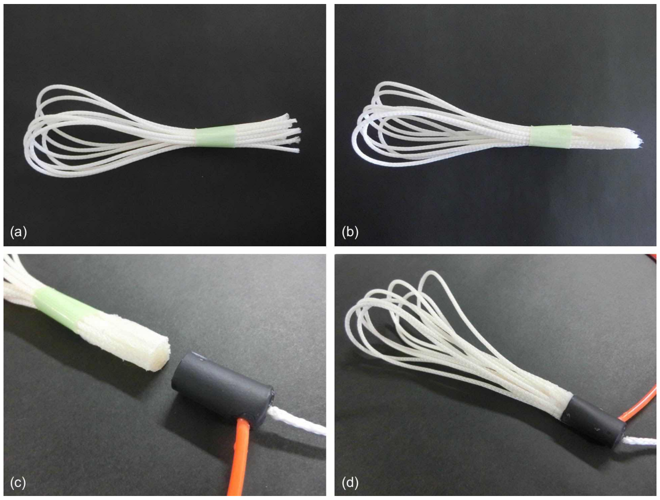

Fig. 5. Manufacturing process to fabricate a multifilament PAM with four main steps corresponding to (a) cutting muscle fibers and assembling, (b) adding silicone to seal one end of the multifilament PAM, (c) cutting the end of the muscle to enable air flow into all muscle fibers and preparing the end cap, and (d) adding and sealing the end cap.

flavum is difficult to see, and the reader is referred to Figure 4 for a better visualization. It should be noted that the nuchal ligament is not shown in Figures 3 or 4 since it was incorporated during the final stages of the complete neck assembly, after the muscles were added.

The structure of the artificial neck with ligaments and bones was found to provide a deformation equivalent to that of the human neck in terms of both frontal flexion and extension, rotation and lateral flexion. Deformation of the artificial neck in flexion and extension is shown in Figure 4, where the arch described by the neck when bending is clearly visible.

Interestingly, the functions of the various ligaments can appear to present a degree of redundancy. For example, the ligamentum flavum is parallel to the posterior longitudinal ligament and their functions appear to be similar. However, the functions of the different ligaments are generally different, and in this work all ligaments were found to be required in order to obtain a deformation of the structure equivalent to that of the human neck. In particular, the posterior longitudinal ligament was found to be relevant in holding the bodies of the vertebrae together, while the ligamentum flavum was found to be necessary to maintain a suitable deformation in forward flexion of the artificial neck, following a similar bending arch to that of the human neck.

C. *Muscles*

The main purpose of the muscles is to provide actuation of the neck. Interestingly, in the human neck, the muscles also serve to protect the viscera in the neck and to help the spine support the head. In this work, the primary focus is on the actuation function, and secondarily on the support function.

The main muscles of the human neck can be organized into three groups [16] as summarized in Figure 2. The first group, which corresponds to the suboccipital muscles,

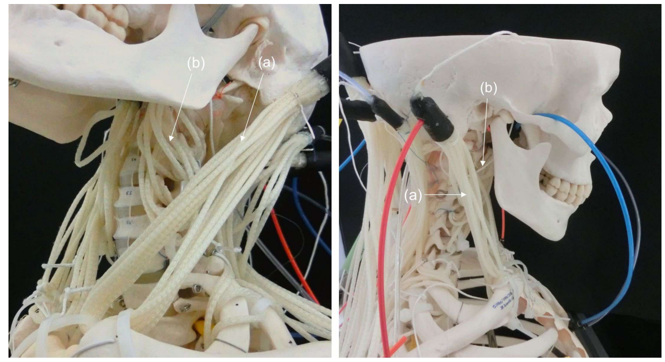

Fig. 6. Two views of the artificial muscles mimicking the anterior neck muscles. The labeled muscles correspond to (a) sternocleidomastoid, and (b) longus capitis and longus cervicis.

includes the rectus capitis minor, rectus capitis major, and obliquus capitis. The second group, corresponding to the anterior neck muscles, includes the longus capitis, longus cervicis, and the scalene muscles, both anterior, middle and posterior. The third group, corresponding to the posterior neck muscles, includes the semispinalis, splenius, trapezius, levator scapulae, and sternocleidomastoid. The scalene muscles are mainly involved in elevation of the ribs, rather than for motion of the neck, and therefore were not incorporated in the neck developed in this work. Similarly, the levator scapulae mainly serves to move the scapula, but is not important in the motion of the neck, and therefore was not included in this work.

The muscles were mimicked using multifilament PAMs [14], [15]. These artificial muscles were fabricated manually according to the following process. First, the individual fibers of the muscle were cut from a roll supplied by s-muscle (Okayama, Japan), with part number 1617, and were subsequently arranged in a bundle, as shown in Figure 5 (a). The fibers have an outer diameter (OD) of 2.2 mm, and they were cut with a length double of that required and then folded (Figure 5 (a)) for simplicity in both manufacturing and subsequent assembly into the neck. Then, approximately 2 cm at one end of the bundle of fibers were coated with adhesive silicone TSE392-C, manufactured by Momentive Performance Materials Inc. (Waterford, USA), and bonded together, as shown in Figure 5 (b), creating an approximately circular outer profile. Once the silicone cured, the bonded end of the bundle was cut to leave the ends of the individual fibers open, as shown in Figure 5 (c). An end cap with a similar diameter as the bonded end of the bundle was fabricated using heat-shrinkable tube SUMITUBE™ W3F2, manufactured by Sumitomo Electric Industries Inc. (Osaka, Japan), sealed at one end with a plastic disc and hot glue HB-40S-1K from Taiyo Electric Ind. Co., Ltd. (Fukuyama, Japan), as shown in Figure 5 (c). A 3 mm OD air supply line was added to the cap by making an incision and sealing it with Loctite® 401™ (Dusseldorf, Germany). Finally, both the inside of the end cap and the bonded end of the bundle of fibers were coated with Loctite® 401™, and were inserted into each other by approximately 1.5 cm to provide a strong

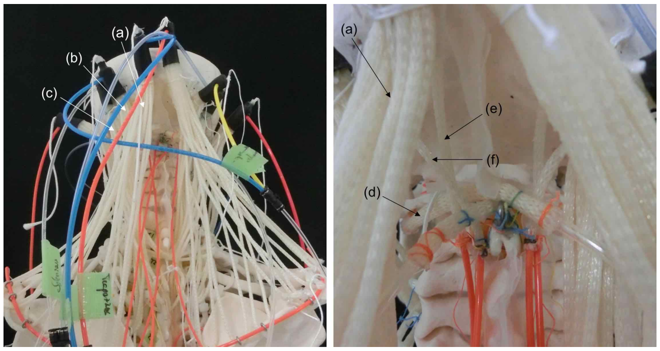

Fig. 7. Artificial muscles mimicking the posterior neck muscles (left) and the suboccipital muscles (right). The labeled muscles correspond to (a) trapezius, (b) semispinalis, (c) splenius, (d) obliquus capitis, (e) rectus capitis minor, and (f) rectus capitis major.

seal, as shown in Figure 5 (d). Heat was applied on the outer part of the heat-shrinkable tube before the Loctite® 401™ was fully cured in order to improve the sealing and prevent any leakage in the final muscle.

The multifilament PAMs were used to mimic the aforementioned human muscles corresponding to muscular groups of the anterior neck and posterior neck, excluding the scalene muscles and the levator scapulae. Individual muscle fibers of 2.2 mm OD were used to mimic the rectus capitis major and minor, whereas individual muscle fibers of 4.2 mm OD, also from s-muscle, were used to mimic the obliquus capitis. The manufacturing process for these individual muscles is similar to that used for the multifilament PAMs, with the difference that the end of the muscle is not coated in silicone, and the end cap is replaced with a segment of heat-shrink tube that connects the muscle with the supply line coaxially.

The dimensions of the artificial muscles were selected to mimic the dimensions of their biological counterparts [17], both in length and diameter. These dimensions were adjusted to the artificial neck by measuring the distances between the insertion points of the different muscles on the artificial structure combining bones and ligaments for the configurations of interest. The performance of the multifilament PAMs [15], [18] resembles that of human muscle [19], [20] in terms of force and contraction, providing a slightly higher force for an equivalent cross sectional area and a somewhat lower contraction. Thus, by mimicking the dimensions of the human muscles, the performance obtained from the artificial muscles in the artificial neck is similar to that of the biological muscles in the human neck. The diameter of the multifilament PAMs was selected with the number of fibers employed in the muscle, with typical values of 14 fibers per muscle.

The insertion points of the artificial muscles were selected to be equivalent to those of the human muscles [16] in order to generate an equivalent neck motion with their actuation. Since the caps in the artificial muscles occupy a portion of the muscle length that does not contribute to the muscle contraction, the region between the cap and the muscle was used for the attachment of one end of the muscles. The attachment to the muscle was achieved by using string made of Dyneema (high-density polyethylene), manufactured by Hayama Ind. Co., Ltd. (Nagahama, Japan) with part number DB-8HE, the other end of which was threaded through holes drilled into the bone in order to obtain accurate attachment points. The opposite end of the multifilament PAMs was attached to the corresponding location using either string or fasteners to affix the loops of the bundles at the desired locations.

The anterior neck artificial muscles assembled into the artificial neck are shown in Figure 6, with corresponding labels. The posterior neck muscles incorporated on the neck are shown in Figure 7 (left), also with corresponding labels. A detail of the rear part of the neck with the suboccipital muscles is shown in Figure 7 (right), with corresponding labels.

D. Integrated neck

The integrated neck was developed starting with the innermost structures, and subsequently adding structures from the inside out. This involved starting with the bones, then adding the majority of ligaments, and finally incorporating the muscles together with some additional ligaments such as the nuchal ligament. The final integrated neck is shown in Figures 6 and 7.

E. Artificial neck actuation

The integrated artificial neck was actuated in order to evaluate the motion capabilities and thus determine the similarities with the motion of the human neck. Muscle groups were activated to provide different motions based on [21] and [17], as summarized in Figure 2. A first muscle group corresponding to the rotation motion was composed of the right semispinalis and splenius, the left sternocleidomastoid, and the right obliquus capitis and rectus capitis major. A second muscle group corresponding to forward flexion was composed of the anterior neck muscles, and both sternocleidomastoid muscles. A third muscle group corresponding to extension of the neck included the trapezius, semispinalis and splenius from both sides, as well as the suboccipital muscles with the exception the obliquus capitis. The last muscle group corresponding to lateral flexion was composed of the right sternocleidomastoid, the right anterior neck muscles, the right obliquus capitis, the right semispinalis, and the right splenius.

The groups of muscles were pressurized gradually, starting at atmospheric pressure and reaching a maximum pressure of 0.3 MPa. The pressure applied to all muscles in a given group was equal. The PAMs act as compliant actuators since, for a given pressure, they provide a relation between contraction and tensioning force, rather than a fixed value for these variables [18]. Thus, the application of a common pressure value to the muscles of each group leads to equilibrium configurations of the artificial neck in a stable manner. The experimental evaluation of the different motions all started with the neck in a central equilibrium configuration, as illustrated in Figures 8 (left), 9 (left), and 10 (left).

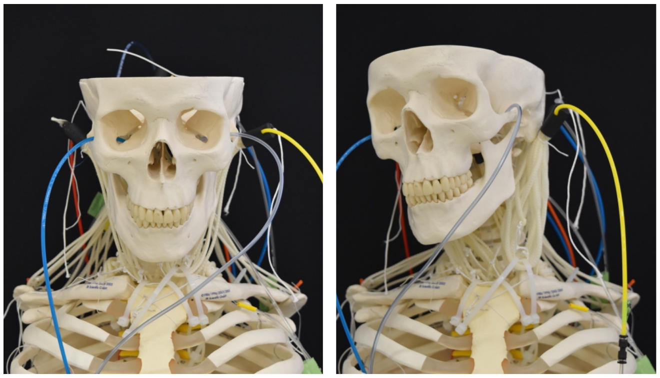

Fig. 8. Results of rotation motion of the neck, with the initial configuration (left) and the final configuration with a pressure of 3 bar supplied at the active muscles (right).

III. Experimental evaluation

The actuation of the artificial neck provided motions similar to those of the human neck, based on visual inspection. The rotation movement resulting from the activation of the corresponding muscle group is shown in Figure 8, including both initial and final configurations. As can be seen, the motion of the artificial neck mimics that of the human neck, as desired.

The resulting motion range in rotation, estimated with the aid of markers inside the artificial cranium, is 25° towards one side. This motion range is lower than that in the equivalent motion in the human neck. This is predominantly due to the fact that the stroke of the PAMs used in this work is limited to approximately 25% of the original length without load [15], which is lower than the stroke of human muscles. This difference in stroke increases when some tension is applied on the muscle. Nonetheless, the type of motion is deemed to be equivalent.

The motion of the neck resulting from the activation of the muscle group corresponding to forward flexion and extension is shown in Figure 9. As can be seen, the artificial neck displays a forward flexion and extension motion similar to that of the human neck. The motion range, estimated based on the difference in orientation of the cranium between Figure 9 (left) and (right), is 50°. As in the previous case, this motion range is lower than that of the human neck, which is also due to the limited stroke of the PAMs employed in this work. However, the type of motion within this available range coincides with that of the human neck.

Finally, the lateral flexion of the neck resulting from the activation of the corresponding muscle group is shown in Figure 10. The artificial neck also exhibits a motion similar to that of the human neck in lateral flexion. The motion range, also estimated based on the difference in orientation between Figure 10 (left) and (right), is 18°. This range of motion is also lower than that of the human neck as a consequence of the limited stroke of the artificial muscles employed.

The characteristics of the artificial neck also mimicked closely those of the human neck [16] in terms of bones, ligaments and muscles, as described in the previous section

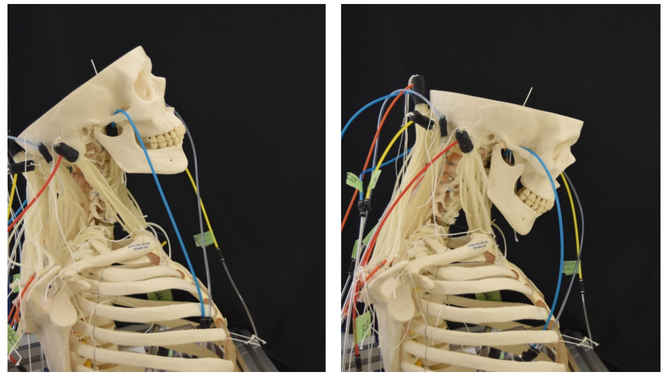

Fig. 9. Results of forward motion of the neck corresponding to extension (left) and rotation (right), both at a pressure of 3 bar in the group of muscles activated in each case.

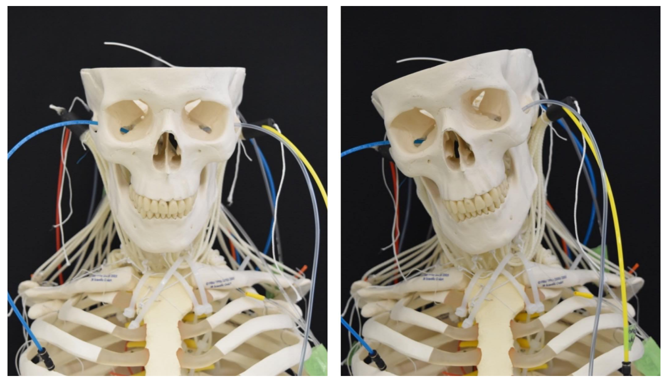

Fig. 10. Results of lateral flexion of the neck, with the initial configuration (left) and the final configuration with a pressure of 3 bar supplied at the active muscles (right).

and shown in Figures 3, 4, 6, and 7. In this regard, the artificial neck met the primary aims of this work in terms of imitating the characteristics of the human neck and reproducing its motions, but leaves room for improvement in other aspects, as discussed in the following section.

IV. Discussion

The experimental results show that the artificial neck provides a motion equivalent to its human counterpart. However, the motion range is lower, approximately half of that of the human neck. As previously mentioned, the main cause for this lower motion range is the limited stroke of the artificial muscles employed.

A degree of improvement in the stroke of multifilament PAMs can be expected in the future, since multifilament PAMs were only recently proposed and their development is still ongoing. As a reference, some of the existing PAMs with the highest stroke can provide near 40% contraction [22]. However, these require significant volume to operate, they can be difficult to manufacture, especially at miniature sizes, and they do not provide the design flexibility required to mimic intricate structures such as the human neck. In this regard, even though improvement in the stroke of multifilament PAMs can be expected in the future, it is likely to be lower than 40% contraction.

A potential alternative to increase the range of motion that can be achieved with current multifilament PAMs is to constrain the muscles to follow curved paths. By forcing the muscles to a curved geometry in the neck configuration that corresponds to their contraction, and a less curved geometry in the neck configuration corresponding to their extension, a larger motion range is obtained with the same muscle stroke. This could be applied, for example, to the anterior neck muscles by constraining their middle sections to be closer to the neck. Thus, in forward extension of the neck, the muscles would present a curved shape, whereas in forward flexion the muscles would be practically straight. This arrangement can be observed to some extent in the human anatomy. The practical implementation, however, requires attaching structures to the middle parts of the muscles, which can affect their performance and lead to bursting. Thus, the specific implementation will be addressed in future work.

Bursting of some the multifilament PAMs occurred during the experimental implementation in this work, typically after a few iterations in terms of neck motion. This is considered to be due to the longitudinal compression of unpressurized muscles in some configurations, which can alter the arrangement of the fibers in the muscle braid. This issue can be overcome by increasing the minimum pressure to be above atmospheric pressure. The use of a higher minimum pressure also leads to better stability of the neck, and improves the efficiency of the PAMs [6]. This, however, also introduces forces on the neck that affect the resulting motion, requiring the application of specific pressure values at each muscle to prevent significant deviations in the motion. The determination of these pressure values is beyond the scope of the work reported in this paper.

Since the force of the multifilament PAMs is higher than that of their human counterparts, the muscles in the artificial neck can be expected to be capable of providing more force than that required to move the neck. The external wrenches that can be supported by the artificial neck, and its performance under dynamic effects, were not studied in this work, but will be explored in future work.

V. Conclusion and Future Work

The development of an artificial neck mimicking the human neck was presented in this work. The resulting neck presents characteristics that closely imitate the complex human anatomy in terms of bones, ligaments, and muscles. The development of the neck was possible thanks to the use of multifilament PAMs which, together with artificial bones and ligaments, enable the development of complex structures similar to those found in nature. In this regard, this work also showcased the potential of multifilament PAMs in the advancement of humanoid robots. The main anatomic structures of the human neck in terms of bones, ligaments and muscles were identified. The process to mimic them was presented, including specific details about the manufacturing of multifilament PAMs. The artificial neck was found to be capable of producing motions similar to those of the human neck when equivalent muscles were activated. The motion range was found to be lower than that of the human neck, and the limited stroke was identified as the main cause. Nonetheless, the capabilities shown in this work are considered to demonstrate the potential of multifilament PAMs in humanoid robots, and thus serve as a first step towards their application in more advanced configurations and scenarios.

Future work will tackle the implementation of multifilament PAMs following curved paths. The specific pressure values that must be applied to the muscles to prevent bursting while achieving stable control of the neck will also be determined in future work, together with a more detailed study of accurate pressure control to perform closed-loop control. Finally, dynamic considerations, including the external wrenches that can be supported by the artificial neck, and operation of the neck at different orientations and in the presence of acceleration will also be addressed in future work.

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