A Conceptual Exoskeleton Shoulder Design for the Assistance of Upper Limb Movement

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Abstract. There is an increased interest on wearable technologies for rehabilitation and human augmentation. Systems focusing on the upper limbs are attempting to replicate the musculoskeletal structures found in humans, reproducing existing behaviors and capabilities. The current work is expanding on existing systems with a novel design that ensures the maximum range of motion while at the same time allowing for lockable features ensuring higher manipulation payloads at minimum energy and fatigue costs. An analysis of the biomechanics of the shoulder is being done and a detailed system design for structural as well actuation elements of a parallel mechanism is given. The benefits for the use are discussed of reduced weight, maximum range of motion at minimum energy cost.

Keywords: Exoskeleton Design, Assistive Systems, Wearable Technology.

1 Introduction

There is an increase in the interest of the research community and industry for wearable technologies in recent years. The future prospects offer endless opportunities for the creation of a wide range of technological solutions for human assistance and augmentation. Orthotic and exoskeleton systems have the advantage of allowing for the enhancement of both the disabled and healthy population. As well as being able to provide medical rehabilitation, their ability to deliver repetitive movements for a longer period and at a higher intensity than manual manipulation gives them the potential to be great tools in rehabilitation training as well as in mitigating fatigue in healthy users.

The role of the shoulder complex in the human everyday interaction with its environment is necessary as it is responsible for most of the upper limb's mobility. Any disruption to the function to this area of the musculoskeletal system can prove severely debilitating. As a result, a considerable amount of research has been conducted on the kinesiology and kinematics of the shoulder [1, 2, 4]. However, due to the kinematic complexity of the upper limb, creating a bioinspired model of the shoulder remains a challenge [5, 6].

It is therefore that many existing exoskeleton designs possess the relevant structural features for shoulder articulation by emulating the kinematic requirements of the anatomical ball and socket joint that is the glenohumeral (GH) joint. Usually satisfying the centre of rotation of the shoulder's GH joint, by designing the exoskeleton around the physical shoulder, attempting to maintain the centre of rotation of the system in line with that of the GH joint [8, 9]. A great number of them apply a form of the triaxial spherical linkage kinematics model of a Cardan universal joint [10–12] while some go even further and introduce some form of scapular motion in conjunction with the Cardan model [13].

On the front of actuation the structure of the shoulder's musculoskeletal system is composed of links serially connected to form a kinematically redundant system; as a result, the shoulder is a parallel mechanism. An aspect that has been explored in the form of parallel mechanism shoulder models [4, 7] and new prismatic parallel actuated exoskeletons [14] for a higher control and torque.

Within this context this work is describing the bioinspired design for a novel shoulder exoskeleton for human augmentation. Although other research efforts have looked into replicating the anatomical structures found in humans, little work has been done in using bioinspired techniques to enhance the shoulder capabilities. This work is expanding on the work, of StrongArm FLx nonpowered exoskeleton [15], on the use and stabilization of the scapula and the scapulothoracic (ST) joint with a new design for the ST. The proposed approach will allow the joint to lock in place enabling the user to maintain postures that will engage the ST join for longer periods of time with minimum energy cost and physical straining.

To achieve this, the paper is organized as follows. In Section 2 the biomechanics of the shoulder will be described, covering the musculoskeletal operation of the different elements. In Section 3 the design of the exoskeleton will be analyzed and compared to the findings of the previous section. Finally Section 4 concludes the paper.

2 Biomechanics of the Shoulder

This section introduces the basic biomechanics of the shoulder. The motions are been analyzed so as to allow for easier replication by the exoskeleton design which will be presented in the following section.

In principle the shoulder girdle (SG) is comprised of three linkages; two synovial joints, between the clavicle (collarbone) and scapula (shoulder blade), and a third between the scapula and thorax.

The sternoclavicular (SC) joint is the most proximal of the joints in the shoulder and is the only anatomic joint in the shoulder complex physically attached by ligaments to the trunk at the manubrium of the sternum. It serves as a stabilizer for the movement of the scapula, with which it articulates at the acromioclavicular (AC) joint, limiting its range of motion (ROM) by keeping the scapula at a relatively constant distance, so the shoulder can swing clear of the trunk whilst transmitting part of the limb's weight to the axial skeleton [16]. The scapula needs stabilizing as it is responsible for supporting the arm at the scapulothoracic (ST) joint. It must be noted however, that the ST joint is not a true joint, but rather a functional joint, a point of contact between the anterior surface of the scapula and the posterior aspect of the thorax [1].

The outer part of the scapula, directly below the AC joint, is called the glenoid cavity. This shallow socket hosts the ball of the head of the humerus forming a synovial ball and socket joint, the GH joint. This type of joint suffers from a severe lack of stability. A group of four of the seven scapulohumeral muscles and their tendons, stabilize the shoulder by keeping the head of the humerus in place. Thus, preventing the dislocation of the GH joint. This group is known as the rotator cuff; the supraspinatus, the infraspinatus, teres minor, and the subscapularis muscle.

The Scapular motion involves the synergic movement of the shoulder girdle. This is achieved by the action of specific primary muscles responsible for scapular motion in six different directions, which are summarised in Table 1. Given that muscles can apply only pulling forces in order for the motions to be completed there is the need for synergetic action for these to achieve the movement of the scapula.

Table 1. Scapular Motion and Primary Muscles

Movement of scapula	**Muscles responsible for the movement**
Protraction	Serratus anterior (SA), Pectoralis minor,(Pm) assists
Retraction	Trapezius (middle fibres) (TM), Rhomboid minor (Rm) Rhomboid major (RM)
Elevation	Trapezius (superior fibres) (TS), Levator Scapulae (LS)
Depression	Pectoralis minor (Pm), Trapezius (inferior fibres) (TI), Latissimus dorsi (LD)
Lateral Rotation	Trapezius (superior and inferior fibres), Serratus anterior (lower 5 digitations)

3 Shoulder Exoskeleton Design

In this Section, the concept for the multidirectional actuation of the human upper limb, based on the movement of the SG is proposed. A simple bioinspired design of the exoskeleton shoulder is approached, duplicating the structure of the human skeletal girdle in which articulations and their ligaments have been substituted with homologous mechanical joints for a more predictable stability. Moreover, the muscles actuating the SG are being substituted by appropriately positioned linear actuators and the second part of the section will focus on explaining their selection and positioning. Finally, the support structure that will form the backbone of the motions will be implemented in the form of harnesses and bodily attachments and been described in the third part of the section.

3.1 Shoulder Skeletal Analogues

The SC joint has the mechanical equivalence of an irregular saddle joint that allows for three rotatory degrees of freedom (DoF). To substitute the SC joint a revolute joint allowed to rotate at both ends is introduced. The first rotating end, attached to the sternum, allows for elevation and depression in the frontal plane, the revolute joint (set at a 90 degree angle) allows for protraction and retraction in the horizontal plane and the second revolute end attaches to the clavicle analogue model allowing for posterior clavicular rotation in the sagittal plane [1].

The clavicle attaches to the acromion of the scapula via the AC joint. This gliding, or plane, joint allows for 3 DoF: two translations along the X and Y axes and a rotation around Z. However, due to the observed osteokinematics of the shoulder girdle [1] the AC joint requires of three revolute perpendicular DoF. One accounting for rotation of the scapula in the frontal plane, a second for the internal rotation of the scapula in the horizontal plane and a third one that allows for anterior and posterior tilting in the sagittal plane. Considering these characteristic, the same RRR joint derived for the SC joint is applicable for the AC joint, despite them being distinct types of synovial joints.

To avoid the necessity and therefore inclusion of the rotator cuff muscles as stabilizing agents, the GH ball and socket joint has been substituted by a gimbal system that is mechanically secured at two points without the need for any further stabilizing anchors. This design provides the stability and the DOF's necessary. The gimbal is set such that the full ROM of the system is utilized, by attaching an extreme of the gimbal's range to the humerus analogue, parallel to the sagital plain to the side of the body. This arrangement allows for the $100^{\circ}$of motion the gimbal is capable of in the frontal plane for glenohumeral abduction. This poses a lack of range in that orientation of 20°according to [1]. However, the actual kinematic values among persons and studies vary considerably, likely due to the different levels of flexibility of the subjects.

This leads to the scapulohumeral rhythm, where the rotation of the scapula is introduced to support the abduction of the arm with an approximate extra 60°, for a full $180^{\circ}$of range, or 160°in the case of the designed system. The retroversion of the humeral head, that aligns the humeral head with the scapular plane for articulation, needs to be accounted for. The gimbal joint is capable of a full 360°ROM perpendicular to the sagittal plane (with the exception of the angle range in which the body is located), since the scapular analogue will be behind the subject's shoulder and therefore positioned further behind with respect to the frontal plane than the humerus analogue and upper arm attachments.

Finally since the focus of the study is on the shoulder region the motion of the elbow is addressed only in as a passive component meant to aid and support humeral internal rotation.

3.2 Shoulder Muscular Analogues

The actuators are placed as to substitute the muscles of the shoulder musculoskeletal system suppressing stabilizing muscles unnecessary in a mechanical system and conserving those responsible for the primary force driving the actions.

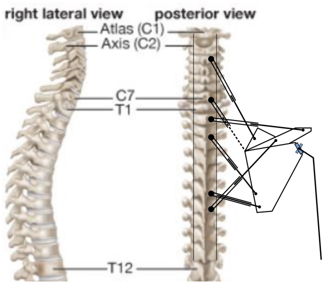

Fig. 1. Origin and insertion of muscle analog prismatic actuators of the posterior scapulothorathic motion.

Fig. 1, represents the substitution of the muscles in Table 1. From the top following the vertebrae, the LS actuator originates from in between the C2 and C3 vertebrae, equivalent to the center of the LS biological origin. The TS originates from the external occipital protuberance and the nuchal ligament, it doesn't have an attachment to a solid surface. Althought the TS aids in scapular elevation, it has its insertion at the clavicle and provides mostly neck movement function rather than scapular. Therefore, the functions of this muscle have been assumed by the LS in the design.

The Rm shown as a dotted line (Fig. 1) is attached in between the C7 and T1 vertebrae and inserts at the root of the scapular spine. Due to the quasi parallel nature of the rhomboids and LS, the functions of the Rm are suppressed and adopted by it's neighboring muscles. Next the TM originates at T2 and inserts at the medial end of the spine close to the acromium. The RM originates between T3 and T4 and inserts at the medial border of the scapula. These muscles in each of their corresponding motions act both as agonists and antagonists. Taking advantage of this aspect, the inclusion of a serratus anterior analogue can be placed at the posterior aspect of the body rather than the anterior. The analogue muscle, prismatic actuator, responsible for its motion will push instead of pulling. The antagonistic analogue inserts at the meeting point between the medial border and the inferior angle of the scapula, originating at T7. This experimental placement satisfies the rotational and the protraction trajectories. For the latter trajectory, the RM and TI muscles join in an antagonist pushing motion to provide a controlled protraction of the shoulder. The modelled TI originates at T8 and inserts at the medial third of the spine.

The LD crosses the inferior angle of the scapula. However, a study found that out of 100 cadavers dissected 57% had a less than substantial amount of muscular fibers originating from the scapula [17]. Therefore, the latissimus dorsi won't be accounted for during scapular motion.

All of the scapular motion prismatic actuators attach with a revolute joint that allows for rotation in the frontal plane, and insert with a universal joint to allow internal rotation of the scapula during protraction.

3.3 Glenohumeral Actuation

The design responsible for GH abduction/adduction has been approached in the same direct substitution fashion for the DA and DP muscles. The DA originates at the anterior border of the lateral third of the clavicle and the DP originates at the spine of the scapula. Both muscles and actuators insert at the deltoid tuberosity of the humerus (Fig. 2).

The deltoid middle fibers (DM) originate at the acromion and insert at the deltoid tuberosity of the humerus, whereas the SS originates at the supraspinatus fossa and inserts at the superior facet of the greater tubercle (Fig. 2 and 3). These two muscles work in synergy; the SS initiates abduction and stabilizes the GH joint as the DM completes the GH abduction.

For this substitution to be possible, the actuator for both muscles would have to be flexible to wrap over the GH joint. The proposed design for this group of two muscles is to fuse their function together at the SS position as shown in Fig. 2. Consequently, to achieve the displacement necessary for the GH abduction, a lever is introduced at the head of the humerus oriented at 110 ° with respect to the lateral aspect of the humerus, taking the elbow as 0°. Thus, can the actuator pull the lever behind the shoulder unobstructed, increasing the length of the lever and placing the insertion further from the fulcrum, increasing the leverage exerted on the humerus.

The LD actuator has a wide origin from the T7 to the L5 vertebrae as well as at the lower four ribs and the posterior third of the iliac crest. As a preliminary origin, the actuator will be attached at the position of the iliac crest. This actuator origin will also be off-set from the body at a distance as to preserve alignment with the rest of the exoskeleton, while allowing space for the actuator to follow the humerus without colliding with the user as the arm is flexed.

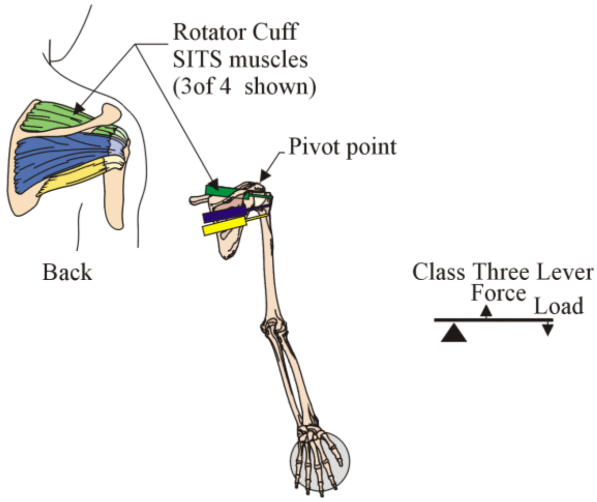

Fig. 2. The shoulder joint is a class three lever system (Supraspinatus: green Infraspinatus: blue Teres minor: yellow) [3].

The insertion of the LD, together with the rest of the muscles responsible for rotation, poses a design problem. The posterior muscles wrap around the humerus and insert on the anterior aspect together with the muscles on the anterior aspect of the torso (Fig. 3). Making an ergonomic design for these actuators is the next challenging step in the design and development of the exoskeleton.

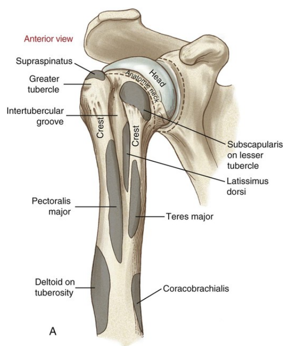

Fig. 3. Anterior view (A) of the right humerus [1].

3.4 Harness and Bodily Attachments

A suitable support system for the actuation elements need to be developed and form part of the exoskeleton design. The proposed system needs to replicate the anchoring characteristics of the biological musculoskeletal system and its operation. With this in mind a bioinspired system is being proposed that is using the same anchoring points along the spinal column.

From a posterior view of the torso, a solid spine (Fig. 4) is attached to the back via a posture brace, or corrector. The brace pulls the shoulders back and straightens the spine to prevent slouching and improve posture. The inferior aspect of the spine attaches to a lumbar pad and is secured to the waist via a safety rock climbing sitting harness, which ensures a reduced displacement of the belt via the adjustable leg perimeter straps. This combination generates a posture feedback system. As the user extends beyond proper posture, the feedback system then provides a gentle reminder, via pressure at the shoulder straps and the spine right above where the back curves in the most, approximately between the T1 and T5 vertebrae, as well as at the lumbar pads. This pressure suggests to the user an adjustment in his or her posture to a correct position.

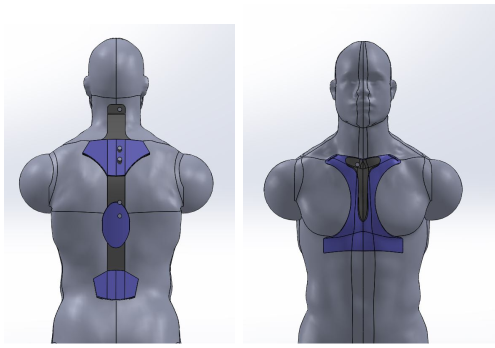

Fig. 4. Exoskeleton support structures. Left - A solid spine is attached to the back via a posture brace. Right - A narrow front chest support to the front. In both the anchoring points for the actuators can be seen. (Image produced in SolidWorks)

This design feature is inspired by the Strongman FLx which is designed to help remind wearers to maintain proper posture, helping to ensure proper lifting technique [15]. With this system the aim is to provide posture support and feedback. Minimising poor posture and over rotation, the adoption and inclusion of this design aims to provide a stable anchoring for the shoulder exoskeleton to the back of the user.

The superior end of the spine culminates in a tongue shape that provides the anchoring for the origin of the muscles attached at the cervical section of the spine.

From an anterior perspective, a narrow front chest support (Fig. 4.) attaches to the posture brace straps at the shoulders. Its inferior aspect, attaches to a second belt extending around the chest and connecting at the thoracic pads of the spine. The chest support houses the mechanical analogue of the sternum to which the clavicle connects to the scapula analogue. Two vertical torso adjusters lock into place from the chest belt to the waist belt preventing slippage. This arrangement completes a 5-point adjustable system. At its centre, the chest belt, a 5-point seat belt racing harness with a quick release centre buckle allows for an easy and immediate detachment.

It is proposed that the harness will follow a fitting approach similar to everyday backpacks. This aims to ensure that the harness will be close to the body, ensuring minimal discomfort and the potential of injury. The key straps are the shoulder ones that provide overall alignment while the rest ensure correct position

The upper arm brace consists of a link that attaches at the bottom of the biceps, the distal end of the humerus, right above the elbow. This location is the point at which the circumference of the upper arm remains at its lowest when performing movements such as an arm curl, thus avoiding major discomfort while performing daily life arm movements while wearing the suit.

The distal placement of the attachment also provides the biggest leverage Include classical lever physics reference on the glenohumeral articulation and thus the shoulder complex, further justifying the placement of the attachment.

A second brace is included at the medial end of the arm under the deltoid insertion at an angle to guide the strap over the top of the biceps brachii muscle accommodating an unobstructed curl of the arm with minimal discomfort. This attachment, works as a stabilising agent tot the humeral shaft of the system by keeping the shaft parallel to the humerus. This inclusion was necessary, since the attachments allow for some displacement, as their flesh anchoring surfaces can be compressed, allowing the humerus to shift and slide under the skin. By increasing the number of attachments, the displacement is reduced.

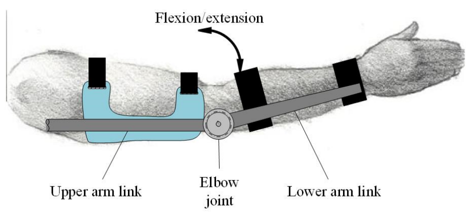

Fig. 5. Proposed passive elbow exoskeleton.

To ensure the compliance of the exoskeleton during internal and external rotations of the humerus in the horizontal plane's axis of rotation, a mechanical link corresponding to the forearm is introduced, leading to the inclusion of braces at the forearm and the wrist. The two links are connected by a revolute joint, coaxial with the humeroulnar (HU) elbow joint, as shown in Fig. 5. With the attachment of the foreanrm link, the extra section applies leverage on the humerus shaft upon rotation, ensuring the complient motion of the model so long as the forearm is at an angle with the humerus. This remains true even in a fully stretched arm, albeit to a smaller degree.

Finally, in Fig. 6 the complete assembly of the proposed system can be seen, with the placement of the actuators and support structures on the harnesses and attachments.

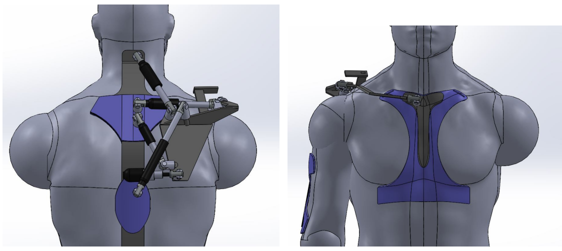

Fig. 6. Front and back view of the complete proposed system.(Image produced in SolidWorks)

4 Discussion and Future Works

To duplicate the motion of the human arm, shoulder exoskeletons are mostly designed around the three principal DOFs of the GH joint. Note that this GH model does not include translation of the glenohumeral joint caused by SC, AC, and ST motions; it's purely rotational. Upon observation, it can be seen that these designs, with or without scapular motion inclusion, rely on a single rotary actuator at its only anchoring point (to the user, rig, wall, etc.). This flaw puts all the strain of the load applied to the exoskeleton during abduction at this specific point, meaning that you will require a large motor that can bear it and still function when attempting to lift large loads.

The exoskeleton design can share the load of an action in every direction between a number of actuators, similar to the way the human body does. The key difference is that the linear actuators in the exoskeleton can perform not only pull but push and locking actions as well. This allows for a versatile use of the suit in different lifting conditions for different tasks. Moreover, due to its parallel design and it's multiple anchoring positions to the body, the design has the aim to reduce injuries due to malfunction, as the system would mechanically constraint itself, not allowing the exoskeleton to perform extreme movements at the edge of the user's arm's ROM.

To attain this ideal design however, an ergonomic solution must be explored to accommodate, in a nonobstructive way, the actuators for the rotation of the humerus at different orientations and positions. Simulations will also be necessary to determine the inclusion of the Rm actuator and the TS actuator necessary for scapular and clavicular stabilization respectively. Determining which actuators offer a stabilization purpose in the shoulder complex, unnecessary in a mechanical analogue design, will be essential. Removing unnecessary actuators from the design would reduce the total weight and bulk of the ensuing system, making it more energy effcient.

To further the security aspect of the design, the harness, should include a tension system; as the front distance decreases upon bending, the distance at the back increases. This way, the chest-rig would remain in place when bending over to any degree, avoiding asphyxiation via the chest rig, and improving the general stability of the harness.

5 Conclusion

This paper presented a novel conceptual robotic exoskeleton design composed of a shoulder and an arm exoskeletal structure to enable maximum range of motion while at the same time allowing for lockable features ensuring higher manipulation payloads at minimum energy and fatigue costs. This robotic exoskeleton has been designed by considering the various motions that the operator will be performing including flexion, extension, abduction, adduction and expands on current exoskeleton designs mainly focusing on existing behaviors and capabilities. Most of the reviewed devices are technically advanced, yet there is still significant need to enhance their efficiencies and reduce their cost [18]. With the design presented, dynamic force to the articulations can be provided to the upper limb by means of a set of motors in combination with a parallel mechanism. The ability to apply internal dynamic forces to the upper limb can potentially widen robotic exoskeleton applications. For instance, they could provide restoration or maintenance of motor function to different joints of the upper limb and at the same time augmenting human performances abilities. Current powered orthoses designed are nonambulatory devices [19] and therefore there is a need in the rehabilitation area of ambulatory devices capable to provide dynamic forces to the upper limb.

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