PRACTICAL DESIGN OF FULL BODY EXOSKELETONS
Stretching the Limits of Weight and Power

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Abstract: The development of full body, wearable exoskeletons has been limited by the constraints of weight and available power. Because of this it has not been possible to create one that augments all DoF of its human wearer with enough power to assist, e.g., nurses and other workers. To achieve more usefulness despite the limitations, a practical design approach that considers the motions and needs of the wearer is an appropriate tool to reveal new opportunities. This approach was used to find solutions for a fully supported 3DoF exo-spine, supported shoulder girdle motion, and other challenges that have so far received little or no attention. No extra actuators are required, thus adding a minimum to weight and power. The improvements found using this practical approach suggest related fields like rehabilitation could profit as well.

1 INTRODUCTION

Recent levels of technology have enabled the creation of various exoskeletal devices: robots that surround (parts of) a human wearer in order to assist him in his movements. Applications range from rehabilitation to strengthening nurses and others in their work. Yet, the all-round applicability of fully wearable, i.e. also energetically autonomous, and particularly full body exoskeletons, has so far been limited by the low amount of degrees of freedom (DoFs) and actuators achievable in such devices.

Increasing the applicability requires augmentation of more human DoFs. This necessitates adding heavy actuators and an accordingly larger power supply for a running time of perhaps a few hours. The more useful and thus larger the device the more unlikely it is to fit in the settings of a hospital or home, and hence designers were forced to limit the abilities of their exoskeletons.

Considering the needs of aging societies to take care of the older generations, this research focuses on exoskeletons for augmentation of nurses and other workers, and has a long term goal to develop a version for physically challenged patients. It is based on the full body robot suit HAL-5 from which a lower body suit was derived for patients who have difficulties walking (Suzuki et al. 2005).

To arrive at new solutions, this paper reviews existing exoskeletons, shows why and how we should change our design approach, and, to show the effectiveness of the new approach, proposes solutions from a mechanical perspective that maximize the capabilities of full body robot suits.

1.1 Existing Exoskeletons

Lower body exoskeletons have been discussed (Dollar & Herr 2008) and few challenges remain. As for the upper body part (from the hip to the hands)

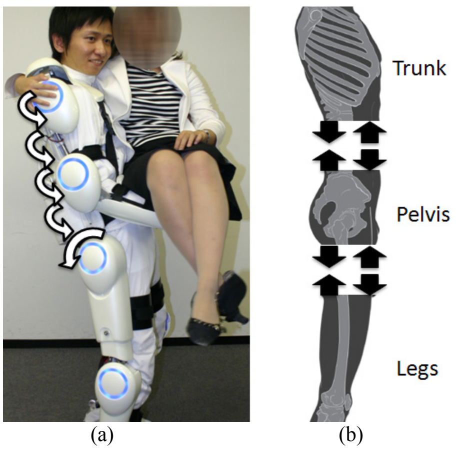

Figure 1: Lifting DoF: the interdependence between hip en trunk moments during lifting, as indicated by the arrows in (a). The interaction forces, (b), between different body parts provide additional proof.

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there are more DoFs and larger workspaces that ultimately compete with the constraints of weight and power. Hence, this is the focus of this review.

One wearable full body exoskeleton is the nurse power suit (Yamamoto 2002). It uses a pneumatic actuator system to augment the muscles used for lifting patients. While it is focused on patient lifting, its workspace, however, is otherwise limited.

Another, the Agri Robot, has not yet appeared in print, but may be found on the web (Toyama 2009). It actuates motors that coincide with the knees, hips, shoulders and elbows according to spoken commands. Its main purpose is helping farmers.

These two exoskeletons, as well as HAL, show exactly how the limitations on weight and power result in augmentation of few DoFs while the shoulder girdle and spine remain immobile.

As for other types, there are several wearable arm exoskeletons that augment all DoFs of the human arms and shoulder girdle (Schiele & Van der Helm 2006) (Folgheraiter et al. 2009). These are for rehabilitation and haptics and require only small output torques. Using such structures to assist lifting, however, would result in larger and heavier devices.

The XOS exoskeleton, manufactured by Sarcos, also remains unpublished (BBC News 2008). This full body suit requires an external power source, but can provide powerful augmentation. The robot's arms only interact with the human at the end effector, thereby allowing the shoulder girdle to move as well.

Another type of exoskeletal devices consists of arms supported on a fixed base. The purpose of such devices differs, but, despite the freedom regarding weight and power, girdle motion has received limited attention (Perry & Rosen 2006) (Liszka 2006).

Lastly, pneumatic muscle actuators have been used in a full body (Tsagarakis & Caldwell 2003) and an upper body exoskeleton (Aida et al. 2009), and have been shown to provide the torque required for lifting. They work like muscles, making them very compatible with humans. The main challenge, however, is to make a wearable power supply.

So far it can be concluded that, using current technology, being wearable and energetically autonomous cannot be combined with having all DoFs active and powerful enough to lift, e.g., patients. Critically, shoulder girdle motion has not been implemented in a full body exoskeleton, and spine motion has not received any attention at all.

1.2 Towards a New HAL

The current full body HAL suit, HAL-5, shown in Fig. 1a, consists of frames interconnected by power units, which each contain an electromotor and reduction gears, positioned directly next to the hip, knee, shoulder (flexion) and elbow joints of the wearer to assist his movements. Additional passive DoFs are located at each shoulder, upper arm, and ankle joint. The suit is powered by batteries.

The system is controlled according to the intentions of the wearer, which are obtained by measuring the bioelectric signal (BES) on the skin above the main flexor and extensor muscles associated with each augmented human joint. Motor torques are calculated according to these signals.

It is expected that similar control techniques and actuators will be used in the new version. In addition, the wearer is assumed to be a healthy person.

Considering the found limitations and the aim to aid nurses, a new design approach for HAL should:

1) Achieve the most practicality given limited technology;
2) Enable handling of patients by nurses, by supporting the forces typically exerted by them.

The word 'practicality' in the first goal implies "fitted for actual work or activities", and is considered the main property to ensures HAL's usability in our human society.

2 A DIFFERENT APPROACH

2.1 Challenges

These goals inevitably pose several specific challenges. Firstly, not actuating some DoFs in order to save weight and power poses the dilemma of creating either passive DoF or a fixed structure instead. Passive means that the wearer will occasionally be required to exert a high degree of effort to handle heavy objects, whereas fixing reduces the human workspace and can result in high forces between the wearer and the robot.

When considering the practical usage of an exoskeleton it may be seen that both during daily tasks (Rosen et al. 2005) and during working (Vieira & Kumar 2004) gravity forces are the most prevalent. Although several exoskeletons specifically counter the forces of gravity during lifting (Suzuki et al. 2005) (Yamamoto, 2002) (Toyama, 2009), this focus also strongly limits the workspace by limiting various DoFs. Moreover, the loads should never be transferred from the suit to the wearer. E.g., as will be shown in section 4, the load supported by the suit may bear upon the wearer's body during walking. Some guarantee that the suit compensates gravity and transfers its weight and that of the carried load directly to the floor is necessary.

Considering patient-handling by nurses it can be seen that pushing and pulling forces are prevalent as well, e.g., when turning a patient around in bed (Schibye et al., 2003). A practical exoskeleton will thus have to be able to support these forces as well.

Next, skin irritation around fastening equipment is a problem not often considered during design, but mostly revealed by experiments (Hidler & Wall 2005) (Colombo et al. 2000). Schiele and Van der Helm (2006) showed how this partly arises from unavoidable misalignments between wearer and robot.

Regarding augmentation of the hands, which would be necessary for picking up heavy objects, it can be seen that only some fully actuated arms have wrist actuators (Schiele & Van der Helm 2006) (Folgheraiter et al. 2009) (Perry & Rosen 2006) whereas for the fingers there are only rehabilitation devices (Sasaki et al. 2004) (Mulas et al. 2005). Unfortunately, all these devices also indicate that it is very difficult to augment fingers up to a practical load of around 25kg for one hand.

Lastly, implementing shoulder girdle and spine movability requires two DoFs for each shoulder and three for the spine, totalling seven extra actuators. This would almost double the amount on HAL.

2.2 A Human Practical Approach

Exoskeletal structures are typically designed using a machine approach, basing the design on the range of motion (RoM) and torques of the human joints that they interact with. For wearable robot suits it seems that with this approach current challenges cannot be overcome. On the other hand, the ways we use our bodies for work reveal characteristics that may provide unknown design opportunities.

In order to discover new solutions this paper posits that, although the number of postures and motions that may be achieved with the many DoFs our bodies provide is very large, we only use a limited subset of them in our daily lives and work because they are somehow optimal. If a robot suit can support this limited, practical set of postures and motions, then it may be considered sufficient.

To illustrate, it is possible for people to eat while maintaining their elbows at shoulder height. People generally avoid this because it is tiring. It is not practical. A practical design approach would therefore consider what the wearer actually needs, wants, and does when wearing an exoskeleton.

What the wearer primarily needs is gravity compensation and the ability to move in ways that tasks may be performed as desired, without feeling the weight of the suit. Also, the suit must know the wearer's intentions, as was realized with HAL's intention based control.

In particular the motions that are desirable or biomechanically optimal or motions otherwise used in practice enable new solutions by requiring HAL to assist only certain, instead of all possible activities. E.g., the way an object is lifted reveals where and when augmentation is required. This is discussed further in the next section.

3 A SEMI-ACTIVE EXO-SPINE

3.1 Unified DoFs

Heavy objects, or patients, are generally too large to hold on one side and are usually held in front of the wearer. Additionally, holding heavy objects on the side with one hand is unbalancing during walking and is not doable beyond normal human strength without sufficient hand augmentation, which, as mentioned, does not exist.

When lifting objects in front the various muscles activated in the hips and back compose several DoFs. However, observing how they are activated, as shown in Fig. 1a, it can be seen that in the hips and back the moments are all generated in the same direction. They act as a single unified DoF.

Some validation can be obtained from Fig. 1b. By separating the trunk, pelvis, and legs the interaction forces can be drawn schematically. This shows that during lifting - knowing that no other external forces are applied to the pelvis - the direction of the moments in the hips must always be the same as throughout the spine. Additionally, this also holds when pushing forward or pulling backward. For ease of reference, this interdependence will be referred to as the 'lifting DoF'.

Extending this concept, it may be seen that adduction and abduction of the shoulder girdle can be included. Abduction is connected to spine flexion, particularly when the body bends down to pick something up, as well as when pushing, and shoulder adduction is connected with spine extension during both lifting and pulling.

3.2 Semi-Active DoFs

It is possible to achieve a similar interdependency in the exoskeleton by using a semi-active DoF. This is a passive DoF driven by an active DoF.

Fig. 2 shows this concept schematically. Normally the stator of a HAL-5 motor moves an arm or leg segment while the axis is fixed to the exoskeleton

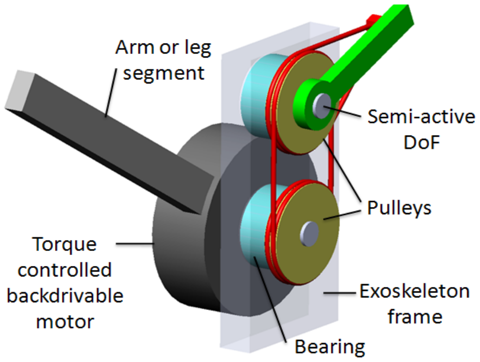

Figure 2: Placing bearings between the exoskeleton frame (transparent) and the axis of a hip (or other) motor while fixing the axis to a pulley, enables the pulley to drive a second, passive joint that thus becomes semi-active.

trunk frame. The axis may instead be connected to a pulley, and be allowed to rotate freely w.r.t. the frame using a bearing. This pulley then drives an otherwise passive joint through cables and a second pulley at this passive joint, much like a common cable actuation system. The torques in the active and the semi-active DoFs are interrelated at any time, thereby creating the desired interdependency.

The motor is, as in HAL-5, torque controlled according to the BES of the wearer's muscles. When applying a semi-active DoF mechanism to assist flexion of the exoskeleton spine, a torque controlled, back-drivable hip motor produces the same force balance in the exoskeleton as in the human lifting DoF. Adding abduction of the shoulder as a second semi-active DoF completes the robotic lifting DoF.

The moment in the human spine, however, decreases when the wearer bends, because the moment arm between the load and the spine, and the moment arm between the load and the hips change unequally. To achieve this effect with the robot, a four-link mechanism between each hip motor and the leg it drives may be used to increase the moment at the robot's legs when the legs are flexed, and thus relatively decrease the moment in the spine.

Considering the ways we lift objects it may also be seen that in a similar way elbow and wrist actuation can be connected using a semi-active DoF, thereby simplifying design.

3.3 Exo-Spine Structure

Using semi-actuation it is possible to support all three DoFs of the spine from both hips. First, just as the two hip moments in a human body act as one moment on the trunk, the two axes of the two hip motors can be connected in order to let the total torque in this single axis act on the robot trunk.

Next, making sure that the exo-spine has a straight neutral position, any deviation should cause a moment that tends to restore the neutral position. This is applicable to each spinal DoF because when the wearer lifts something support is required in all directions in order to pick it up while being rotated, bend sideways or while using one hand. In effect, all three DoFs are connected into a unified DoF that tends to restore the neutral position.

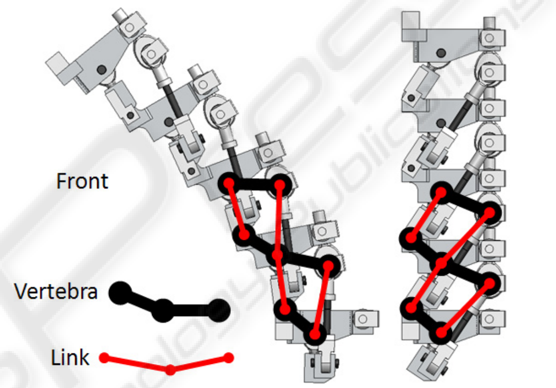

Figure 3: Spine structure composed of vertebrae and links, some overlaid by schematic equivalents, in fully bent and straight positions. It extends when bending forward to accommodate human spine flexion.

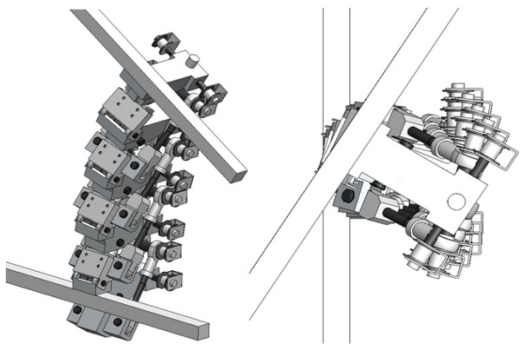

Figure 4: Side bending (a) and rotation (b) (top view) of the spine structure. Beams were added for clarification.

A suitable spine-like mechanism is shown in Figs. 3 and 4. The details of the design are beyond the scope of this paper, but it can be seen that all three DoFs of the human spine are provided. Several vertebra-like segments and links are interconnected by ball joints, while two synthetic cables (not shown) connected to the axes of the hip motors pull the structure towards the neutral position. The cables continue from the spine upwards to support against shoulder girdle abduction during lifting and pulling.

The connected axes of the hips are balanced in only one direction. In the other direction a torque-clutch locks the axes of the motors to the frame, depending on the direction of the combined torque produced by the motors and the cables.

Given sufficient motor torque, the exo-spine is analyzed using FEM to be strong enough to support 80kg at 24cm in front of the center of the wearer, which would relieve most of a nurse's load. Moreover, all forces applied to the wearer pull towards the neutral position, and hyperexten-sion is blocked, making it safe to use. The exo-spine requires no extra actuators, provides gravity compensation, and supports pulling and pushing as required, utilizing practical human mechanics.

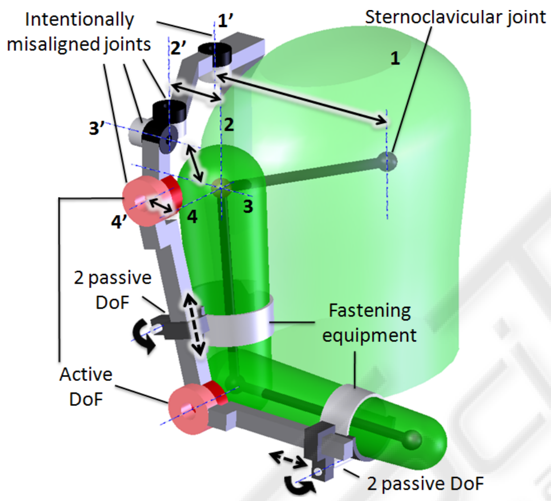

Figure 5: Schematic CAD model of the trunk and one arm. Robotic joints 1'- 4' do not align with the sternocla-vicular joint (1) and the glenohumeral joint (2-4). Motions between the human and the robot at the fastening equipments are accommodated by extra passive DoF.

4 OTHER SOLUTIONS

4.1 Intentional Misalignment

Two passive DoF added after each active arm joint as proposed by Schiele and Van der Helm (2006) not only facilitate unavoidable misalignments between the robot and human joints, they also allows larger misalignments. Using this concept, offsetting the three robot joints at the shoulder w.r.t. the glenohumeral joint would create space for the wearer's shoulder girdle to move upward, without the need to actuate such a DoF. This increases the RoM of the arm, since raising the arm beyond about 90 degrees involves upward motion of the girdle.

Fig. 5 illustrates this. Robot axes 1', 2', 3', and 4' have been misaligned intentionally w.r.t. their human counterparts. Axis 1' facilitates girdle abduction, supported by the same cables as the exo-spine. It has a large misalignment, but a small RoM, allowing it to function as desired. Due to the added passive DoFs the moment effectively put on the human arm for a constant motor torque differs by a few percent according to the posture. This is often disrupting for machines, but is not sufficient to influence the wearer of an exoskeleton.

4.2 Gravity Compensation

The human arm has a large workspace, but only some of the robot arm's DoFs can be active, and they must always be positioned such that they compensate gravity forces when required. In general, people often lift objects with their elbows kept down as much as possible, e.g. as farmers do (Nevala-Puranen 1995). Assuming this, an arrangement of passive and active DoFs as shown in Fig. 5 would let the output of each motor compensate gravity as much as possible. This is because the axes of the motors are always perpendicular both to the gravity forces as well as to the line connecting the center of the motor to the point where the load is applied.

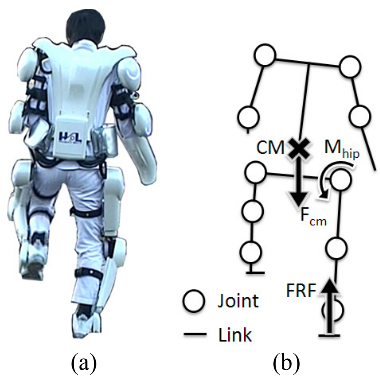

Figure 6: Single stance phase during stair climbing with HAL (a). A model (b) shows how the force (F_{cm}) at the center of mass (CM) and the floor reaction force (FRF) create a moment at the hip joint of the stance leg, M_{hip}.

At the hips, forces acting from the back part of the suit are supported by the suit's legs. Standing on both legs is no problem, but when walking, during the single stance phase as shown in Fig. 6, a large moment, about 2Nm/kg, is developed around the hip of the stance leg. Because nurses on occasion need to walk when lifting, these moments should be supported. However, it is also desirable that the wearer be able to abduct the leg. Passive joints that only allow abduction of the legs would solve this.

5 DISCUSSION

Even with the proposed solutions the variety of motions that can be performed with HAL is still less than without, and limitations remain. Gravity compensation is limited to generic postures, some useful DoFs, such as inner rotation of the arm, are not augmented, and the full RoMs are not achieved.

Even so, in most working situations there are several postures available to the worker by which the task's goals can be achieved, and the wearer may adapt his motion to utilize postures for which HAL provides the most support. Since this is available in postures humans use extensively it is very likely that, although it should be confirmed by further research, at any time at least one good posture can be attained.

Therefore, HAL would be valuable in a human environment and the proposed practical design approach thus achieved its goals. In addition, it is expected that further practical, human characteristics may be exploited to simplify design.

We believe that a similar practical focus may be applied to other fields where humans and machines meet cooperatively, such as rehabilitation, to yield new improvements. A practical approach could unveil solutions that enable patients to perform particularly those motions needed for daily activities.

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