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Compliant Actuation of Exoskeletons[1]

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1. Introduction

This chapter discusses the advantages and feasibility of using compliant actuators in exoskeletons. We designed compliant actuation for use in a gait rehabilitation robot. In such a gait rehabilitation robot large forces are required to support the patient. In case of post-stroke patients only the affected leg has to be supported while the movement of the unaffected leg should not be hindered. Not hindering the motions of one of the legs means that mechanical impedance of the robot should be minimal. The combination of large support forces and minimal impedances can be realised by impedance or admittance control. We chose for impedance control. The consequence of this choice is that the mass of the exoskeleton including its actuation should be minimized and sufficient high force bandwidth of the actuation is required. Compliant actuation has advantages compared to non compliant actuation in case both high forces and a high force tracking bandwidth are required. Series elastic actuation and pneumatics are well known examples of compliant actuators. Both types of compliant actuators are described with a general model of compliant actuation. They are compared in terms of this general model and also experimentally. Series elastic actuation appears to perform slightly better than pneumatic actuation and is much simpler to control. In an alternative design the motors were removed from the exoskeleton to further minimize the mass of the exoskeleton. These motors drove an elastic joint using flexible Bowden cables. The force bandwidth and the minimal impedance of this distributed series elastic joint actuation were within the requirements for a gait rehabilitation robot.

1.1 Exoskeleton robots

Exoskeletons are a specific type of robots meant for interaction with human limbs. As the name indicates, these robots are basically an actuated skeleton-like external supportive structure. Such robots are usually meant for:

- Extending or replacing human performance, for example in military equipment (Lemley 2002), or rehabilitation of impaired function (Pratt et al. 2004),
- Interfacing; creating physical contact with an illusionary physical environment or object; these *haptic* devices are usually referred to as kinaesthetic interfaces. Possible applications appear for example in gaming and advanced fitness equipment, or in

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creating 'telepresence' for dealing with hazardous material or difficult circumstances from a safe distance (Schiele and Visentin 2003).

• Training human motor skills, for example in the rehabilitation of arm functionality (Tsagarakis and Caldwell 2003) or gait (Colombo et al. 2002) after a stroke.

Every typical application has specific demands from a mechatronical design viewpoint. Robots in interaction with human beings should be perceived as compliant robots, i.e. humans should be able to affect the robots motions. In other words, the soft robots should have an impedance (or admittance) control mode, sensing the actions of the human beings. Since the impedance or admittance control does not need to be stiff but compliant we can use compliant actuators. An advantage of compliant actuators is that the impedance at higher frequencies is determined by the intrinsic compliance of these actuators. For non compliant actuators the impedance for frequencies higher than the control bandwidth is determined by the reflected motor mass. In general, the impedance of the reflected motor mass will be much higher than intrinsic compliance of compliant actuators, especially when the needed motor torques and powers will be high. The advantage of compliant actuators is that they not only have a favourable disturbance rejection mode (through the compliance), but also have sufficient force tracking bandwidth. The compliant actuators discussed in this article were evaluated for use in an exoskeleton for gait training purpose, but might find wider application. First of all the specific application will be described, followed by models and achieved performance of the actuators.

1.2 Context: a gait rehabilitation robot

We are developing a LOwer-extremity Powered ExoSkeleton (LOPES) to function as a gait training robot. The target group consists of patients with impaired motor function due to a stroke (CVA). The robot is built for use in training on a treadmill. As a 'robotic therapist' LOPES is meant to make rehabilitation more effective for patients and less demanding for physical therapists. This claim is based on the assumptions that:

• Intensive training improves both neuromuscular function and all day living functionality(Kwakkel et al. 2002; Kwakkel et al. 2004),
• A robot does not have to be less effective in training a patient than a therapist (Reinkensmeyer et al. 2004; Richards et al. 2004),
• A well reproducible and quantifiable training program, as is feasible in robot assisted training, would help to obtain clinical evidence and might improve training quality (Reinkensmeyer et al. 2004).

The main functionality of LOPES will be replacing the physiotherapists' mechanical interaction with patients, while leaving clinical decisions to the therapists' judgment. The mechanical interaction mainly consists of assistance in leg movements in the forward and sideward direction and in keeping balance.

Within the LOPES project, it has been decided to connect the limbs of the patient to an 'exoskeleton' so that robot and patient move in parallel, while walking on a treadmill. This exoskeleton (Fig. 1) is actuated in order to realize well-chosen and adaptable supportive actions that prevent fail mechanisms in walking, e.g. assuring enough foot clearance, stabilizing the knee, shifting the weight in time, et cetera. A general aim is to allow the patient to walk as unhindered as possible, while offering a minimum of necessary support and a safe training environment. Depending on the training goals, some form of kinaesthetic environment has to be added. This constitutes the main difference between LOPES and the commercially available gait-trainers. Those are either position controlled devices that overrule the patient and/or allow only limited motions due to a limited number of degrees of freedom, and/or are not fully actuated (Hesse et al.

2003). Position controlled devices omit the training challenges of keeping balance and taking initiative in training. More research groups have recognized this shortcoming (Riener et al. 2005).

In the control design of the exoskeleton in general two 'extreme' ideal modes can be defined, that span the full range of therapeutic interventions demanded in the LOPES project. In one ideal mode, referred to as '*robot in charge*', the robot should be able to enforce a desired walking pattern, defined by parameters like walking speed and step-length. This can be technically characterized as a high impedance control mode. In the other ideal mode, referred to as '*patient in charge*' the robot should be able to follow the walking patient while hardly hindering him or her. This can be technically characterized as a low impedance control mode. An intelligent controller or intervention by a therapist then can adjust the actual robot behaviour between these high and low impedance modes.
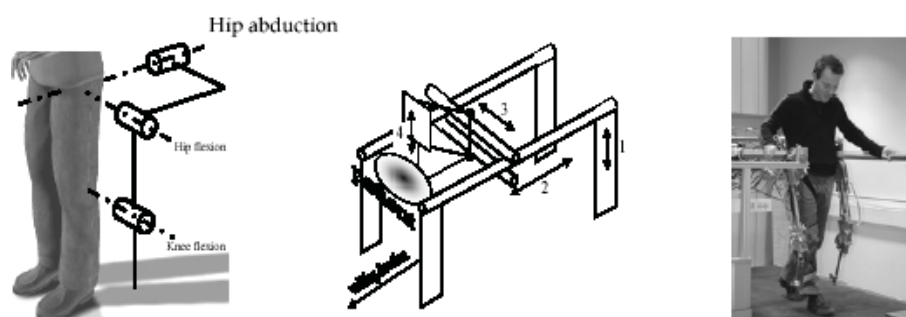

Fig. 1. Design of LOPES. Left: DoFs of the exoskeleton that are actuated. Other DoFs are left free (ankle knee ab/aduction) or constrained (hip and knee endo/exorotation). middle: schematic drawing of the construction for connecting the exo-skeleton to the fixed world consisting of height adjustable frame (1), two sets of parallel bars with carriages for the for-/backward (2) and sideways (3) motion that are both actuated, and a parallogram with weight compensation the allows for vertical pelvic motion as occurs while walking. Right: photo of LOPES.

1.3 Impedance- versus admittance-controlled interactive robots

Many issues arising in the design of interactive neuro-rehabilitation robots are similar to those appearing the field of haptic, or more precise: kinaesthetic robotics (Brown et al. 2003). The characteristic feature of these robots is the bi-directionality of being able to both 'read from' and 'write to' a human user (Hayward and Astley 1996). Such robots are in general meant to display virtual objects or a virtual environment to a user. This user then can interact with a virtual or distant 'world' in a mechanically realistic way.

In contrast, interactive neuro-rehabilitation robots are meant to operate in between both stated modes of 'robot in charge' and 'patient in charge', acting as a 'robotic therapist'; not to display virtual objects as realistic as possible. Another difference, specific for limb-guiding exoskeletons, is that a kinaesthetic display usually has an end-effector that displays the information at one location on the robot, while an exoskeleton necessarily interacts at several points with human limbs as it is connected in parallel to the limbs. This implies that not only an end-effector force is important, but all 'internal' torques over all actuated joints. This all makes it necessary to first select the optimal basic control outline for this kind of robot, as different outlines imply different robot construction and actuator demands.

In general there are two basic ways to realize a kinaesthetic display (Adams and Hannaford 2002); impedance-control-based that is 'measure position and display force' (Fig. 2 left) and admittance-control-based (Fig. 2 right) that is 'measure force and display position', although

hybrid forms exist. The important difference is that in impedance-control the quality of the display will depend on the accuracy of the position sensors and the bandwidth and accuracy of the force servos, and in case of admittance-control on the accuracy of the force sensors and the bandwidth and accuracy of the position servo. The bandwidth of the mentioned servos will depend on both the robot construction and the actuators. The choice between high performance force servo quality and high performance position servo quality puts specific demands on the robot construction and actuation. This choice has to be made even if a hybrid control architecture with both position and force sensing is used. To make clear what this choice basically is about it can also be presented as the choice between a lightweight (and flexible) uncompensated construction and a rigid (and heavy) controller-compensated construction.
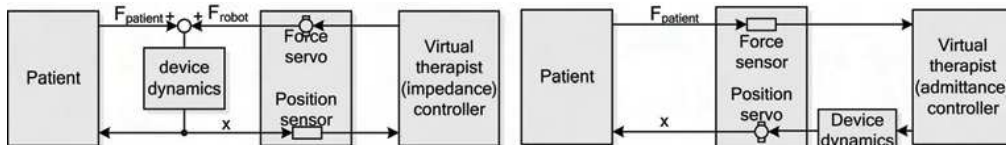

Fig. 2. Basic outline of an impedance-control (left) and admittance-control based rehabilitation robot.

A fundamental limitation of impedance control is that in each specific controlled degree of freedom (or '*dof*') the dynamical behavior of the robot construction in this 'dof' appears in the force transfer ('device dynamics') (Fig. 1). It can only be compensated for in case of a proper dynamical predictive model, and proper measurements of position and velocity for stiffness and friction compensation respectively. Mass compensation is possible to a small extent only, by adding a force or acceleration feedback loop (resulting in a hybrid control architecture). Best results within an impedance-control architecture are obtained using a lightweight, low friction construction and a low impedance actuator, so that the intrinsic mechanical impedance of the device is kept low. Impedance controlled robots typically display 'low-forces' and lack performance in kinaesthetic display of high inertia and high stiffness. (Linde and Lammertse 2003). This is not essential in gait-rehabilitation as no stiff contacts or large inertias have to be displayed, although relatively high forces certainly appear.

An admittance control scheme, on the other hand, demands for a high positioning bandwidth, and therefore for high(-er) power actuators and a stiff construction without backlash (Linde and Lammertse 2003). A limitation of admittance control is that the display of low stiffness ('free motion') can become instable, especially in case of a rather stiff user, because of the high control gains needed in this case. Another limitation is that admittance can only be controlled at the location(-s) of the force sensors. The construction will display its intrinsic impedance at other locations, since the interaction behaviour there cannot be influenced by the controller without force sensing. This might pose a problem for application in neuro-rehabilitation, because of the possible safety threat (for instance for the therapist). The robot will not react to mechanical interactions that by-pass the force sensors. This is all the more important as with admittance control actuators and construction will be considerably heavier.

Summarizing, compared to general kinaesthetic devices a less critical stiffness- and mass-display is demanded and movements are relatively slow. An admittance controlled system imply larger safety threats due to the higher required actuator power, rigidity and inertia of the robot and is less stable when a low stiffness is displayed. Considering all this we choose an impedance-control based design strategy for our exoskeleton. An important advantage is also that the programmed dynamical behaviour will be available everywhere on the construction, that is, in every actuated degree of freedom.

Impedance control implies that the actuators should be perfect force sources, or, realistically, low-impedance, high precision force sources (in contrast with position sources that would be needed for admittance control). The construction therefore should be lightweight, although being able to bear the demanded forces, and should contain less friction. Fig. 3 shows the robot control outline for one degree of freedom (DoF) that is impedance controlled.
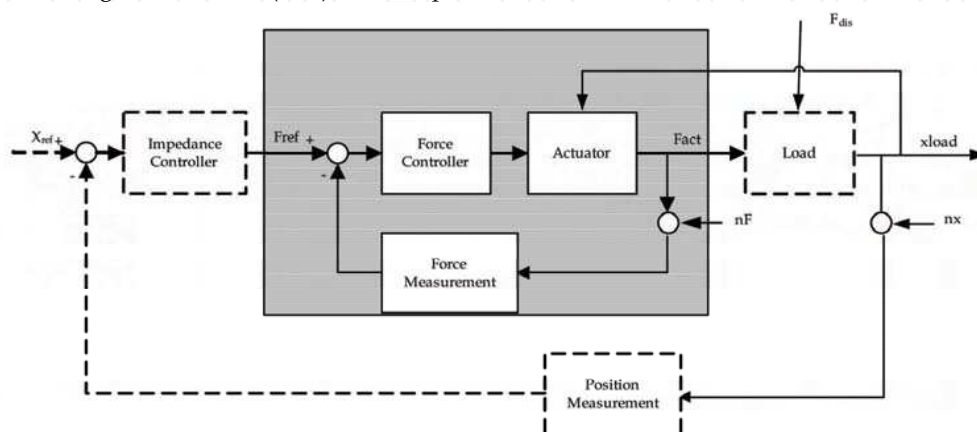

Fig. 3. Schematic control outline for one degree of freedom. The inner loop (shaded area) assures that the actuator acts as a pure force source. The outer loop (impedance controller) sets the force reference based on desired impedance and actual displacement. The load reflects the robot/human-combination dynamics in the considered DoF. In case the actuator is compliant the load displacement directly influences the force output. Symbols: x_{load} – position load; F – force; F_{dis} – external force disturbance; n_F – force sensor noise; n_x – position sensor noise.

1.4 Advantages of compliant actuation in impedance controlled devices with 'high force' demands

As addressed by Robinson (Robinson 2000), commonly used actuators are poor force actuators, even if in many theoretic approaches actuators are supposed to be pure force sources. For small robots common brushless DC motors in combination with cable drives, usually suffice, as for example used in the WAM-arm (Townsend and Guertin 1999), a haptic device. In general, actuators with high force and high power density typically have a high mechanical output impedance due to necessary power transmission (e.g. geared EM motors) or the nature of the actuator (e.g. hydraulics). These actuators do not have a large force tracking bandwidth in case high forces have to be displayed.

The solution suggested by Robinson, and several others (Morrell and Salisbury 1998; Robinson 2000; Bicchi et al. 2001; Sugar 2002; Zinn et al. 2004) is to decouple the dynamics of the actuator and the load, by intentionally placing a compliant element, e.g. a spring, between both. The actuator can then be used in a high gain position control loop, resulting in an accurate control of spring deflection and resulting force, while compensating the internal dynamics of the actuator. The advantage of a compliant element is that it not only filters friction and backlash and other non-idealities in transmission drives from the force output, but also that it absorbs shock loadings from the environment.

An alternative way of realizing such a compliant actuator is to use a pneumatic actuator, which is compliant due to the physics of air. The most straightforward way is by using a

double-acting cylinder, but also an antagonistic pair of fluidic muscles achieves a double acting system (Ferris et al. 2005). Instead of measuring spring-deflection, pressure measurements can be used as indirect force measurement.

Mechanical compliance in the actuation does not offer its advantages without costs. The lower the stiffness, the lower the frequency with which larger output forces can be modulated. This is caused by saturation effects that limit the maximal achievable acceleration of the motor mass and spring length, or by the limited fluid flows for given certain pressures. A limited 'large force bandwidth' decreases in turn the performance in terms of positioning-speed and -accuracy. A careful design and trade-off is needed to suit such actuators for a typical application.

As mentioned by Robinson, it is not yet obvious how to select the proper elastic actuator for a certain application. His general models appeared to be useful for predicting behaviour of a series elastic actuator configuration, but do not clarify what the limitations of several implementations of elastic actuators are. He suggested that important parameters would be the force and power density levels of the specific configuration. To make a proper comparison between series elastic actuators and pneumatic elastic actuators, the latter will have to be described in similar parameters as the first. Once this is achieved the question of the limits and (dis-)advantages of both types of elastic actuation can be addressed.

1.5 Actuator demands in an impedance controlled rehabilitation robot

Impedance control implies specific demands for the actuators in the robot. They should:
- be 'pure' (low impedance) force sources
- add little weight and friction to the moving robot construction in *any* degree of freedom, not only the specific degree of freedom actuated by the considered actuator
- be safe, even in case of failure
- allow fast adjustment to the individual patient's sizes
- be powerful enough for the 'robot in charge' task.

More specific, we decided that the actuators should be able to modulate their output force with 12 Hz for small forces, and 4 Hz for the full force range. Maximum joint moments differ per joint, and range from 25 to 60 Nm. Joint powers range up to 250 Watt per joint. These numbers were based on study of the human gait cycle and the motion control range of a human therapist. An analysis of a nominal gait cycle (Winter 1991) was studied to obtain maximal needed torques, speeds and powers during walking, and general data on human motor control were studied to estimate maximum expected force-control speed and accuracy of a physical therapist.

The resulting actuator bandwidths are typically lower, and the forces typically higher than in the specifications of common kinaesthetic devices which are intended for haptic display of a virtual object, but not to assist humans. Actuators usually selected for kinaesthetic devices are either heavy (like direct drive electro-motors) or poor force actuators (like geared DC motors).

We evaluated different compliant actuators. A series elastic actuator and a pneumatic cylinder were dimensioned to meet the required demands state above. Both type of actuators were modelled, evaluated and compared with each other. Next, we also designed and evaluated a new type of series actuator. To minimize the mass of the exoskeleton we disconnected the motor from the exoskeleton and connected the motor with the elastic joints through Bowden cables.

2. A framework for compliant actuation

In this paragraph we first will derive a general model for compliant actuators. Next we will put pneumatic and series elastic actuation into this general framework.

2.1 General model of a compliant actuator

The first step in comparing compliant actuators is a general model (Fig. 4) that is detailed and flexible enough to describe the essential behaviour of any kind of compliant actuator, in this case both a series elastic actuator based on a brushless DC motor, and a double-acting pneumatic cylinder. The basic element of such an actuator is its elastic element or elasticity that we define as it intrinsic stiffness (K_s). Furthermore it should contain a motor block that modulates spring length or the force. A last important factor is the friction *after* the elastic element, as this (usually complex) friction can hardly be compensated for by a controller. It appears from this scheme that the actual load influences the force tracking performance, as the load displacement (x_{load}) is an input to the system. With this general model, parts can be modelled as complex as seems necessary, or as complex as availability of system parameters allows for. All parameters should of course be transformed to the output axis domain, to fit in the general model.
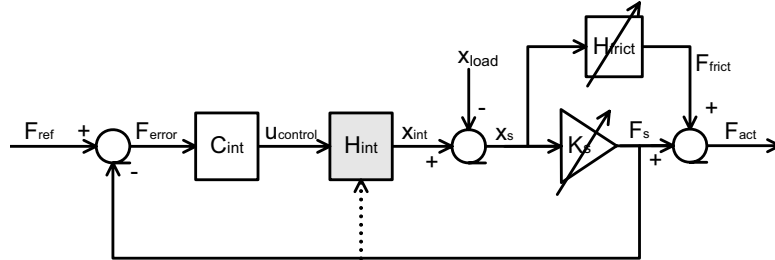

Fig. 4. General model of a compliant actuator, (fitting in the shaded area of Fig. 3), consisting of a controlled (with controller C_{int}) internal position source (H_{int}) a compliant element with (variable) stiffness (K_s) and a (variable) friction model (H_{frict}). These subsystems are possibly non-linear. The force over the spring element F_s is the actually controlled force, because it is intrinsically measured. In case the real output force F_{act} is measured, this measurement should be used for control, so that also the friction can be compensated. Position variables concerning the elastic element are: x_{int} position of the internal side, x_{load} is the load position, x_s the spring length. F_{ref} is the desired reference force, F_{frict} the (external) friction force, whose sign depends on the motion direction.

For every kind of compliant actuator the H_{int} forward path transfer function (H_{fp}) has to be determined. For practical reasons (so that the transfer can be directly measured) the stiffness is included in the transfer. The load impedance is taken infinite corresponding to a fixed load. The H_{frict} is not included as the linear damping in this transfer function can not be measured since the load is fixed:

$$H_{fp}\left(\omega, K_s\right) = \left.\frac{F_{act}}{u_{control}}\right|_{Z_{load} = \infty} = H_{int}(\omega)K_s \tag{1}$$

By applying feedback control the force tracking transfer function for fixed load conditions becomes:

$$H_{force}\left(\omega, K_s\right) = \left.\frac{F_{act}}{F_{ref}}\right|_{Z_{load} = \infty} = \frac{C_{int}H_{int}(\omega)K_s}{1 + C_{int}H_{int}(\omega)K_s} \tag{2}$$

The mechanical output impedance of this controlled actuator is:

$$Z(\omega, K_s) = \frac{F_{act}}{x_{load}} = \frac{-K_s}{1 + K_s C_{int}H_{int}(\omega)} \tag{3}$$

This already shows that, if the $C_{int} \cdot H_{int}$-gain falls off at higher frequencies, the impedance will become equal to $-K_s$ at those frequencies. It also shows that the mechanical output

impedance at lower frequencies can be modulated, as the actuator controller C_{int} appears in the impedance transfer function.

It should be noted that the H_{int} and the H_{frict} will in general not be linear. Saturation effects play an important role in determining the behaviour of elastic actuators. This means that for a prediction of actual performance in a certain operation conditions, H_{int} should be non linear and should contain the saturation characteristics.

2.2 Model of the Pneumatic Cylinder Actuator

For a pneumatic cylinder actuator (Fig. 5) the control problem is relatively complex, because of the fundamental strong nonlinearity in this class of actuators. In a system containing proportional valves, the control input is the valve current, which controls the valve flow area, which depending on actual up- and downstream pressures causes airflow. This airflow depends on the control input, the several flow-restrictions and the actual pressures, that depend on actual chamber volumes. The air flows determine the pressure changes in the two separate actuator chambers. The absolute pressure levels determine the stiffness and the pressure difference in the chambers determine the resulting force output. This results in a relation between the valve current and the chamber pressures that is highly non-linear with respect to the pressure and the chamber volumes.
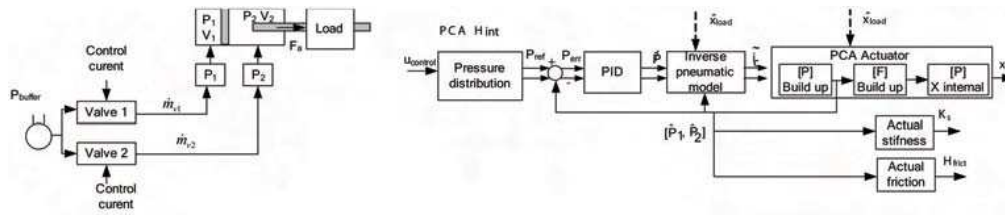

Fig. 5. general outline of the components (left) and the model (right) of a typical pneumatic cylinder actuator (PCA). The force is indirectly controlled by controlling the actuator pressures corresponding to a control command. The double connecting lines are drawn to show that the system contains two valves to control the air supply to both cylinder chambers independently. The actuator is divided into a pressure build-up part, a force build-up part and an internal positon reconstruction part, to clarify the outline of the used model. $\hat{P}$, $\hat{x}_p$ and $\hat{\dot{x}}_p$ are measured input parameters used in the inverse model. $\tilde{i}_c$ indicates the two valve control currents.

When a proper model of the actuator system is available, it is possible to add non-linear blocks that mathematically invert the non-linearities of the pneumatic plant, resulting in an approximately linear system (Richer and Hurmuzlu 2000; Richer and Hurmuzlu 2000; Xiang and Wikander 2004), that is a system consisting of actual parts of the plant in combination with their approximate mathematical inverts. These inverts are also non-linear, and are a function of variables that have to be measured in real-time, like pressure and piston position. After this specific case of feedback linearization (Slotine and Li 1991) model based errors will be introduced that have to be compensated by the PID controller. By controlling the pressure levels independently in both chambers not only the force output but also the effective stiffness can be controlled. We used the model descriptions of Richer (Richer and Hurmuzlu 2000), including valves, tubing and cylinder chambers, and combined them with the block oriented linearization technique as described by Xiang (Xiang and Wikander 2004). It results in an approximately overall linear plant unless the actuator saturates.

2.3 Model of the Series Elastic Actuator

The important advantage of a spring is that it allows treating the force control loop as a position control, because the spring length can be considered proportional to the force output. A higher compliance in the force sensor allows for higher control gains in the feedback spring length control loop. This way a better force control performance and actuator impact resistance can be achieved. Adverse effects of for example backlash and stick in transmissions can also be decreased this way.

To fit a series elastic actuator into the general model (Fig. 4), the appropriate H_{int} and H_{frict} have to be obtained. H_{int} mainly depends on the dynamics of the motor used to drive the actuator, and can be calculated, in case of a brushless DC – driven SEA, with a basic linear motor model, shown in Fig. 6. This model of the SEA neglects all non-linearity, but this is less important as these will be largely compensated by the feedback of the spring length. This does not apply for saturation which will be considered separately. Saturation is an actuator inherent limitation that can not be compensated for.
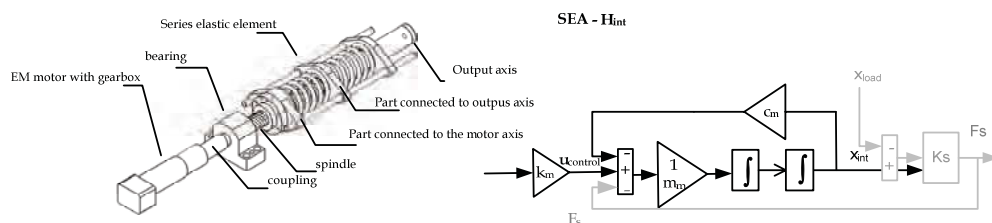

Fig. 6. General outline of the components (left) and the model (right) of the Series Elastic Actuator, with added K_s. Model of a DC-motor as torque source, including motor inertia and damping. k_m is the motor constant, m_m is the motor inertia, c_m the motor damping, including friction components and back-emf of the motor.

The K_s is the physical spring-stiffness. This way all parameters in the H_{int} transfer can be obtained from motor data. For the damping only the back-emf component will be known on beforehand; the damping component of system friction will have to be estimated. The output friction H_{frict} is difficult to obtain during the design phase. For now it will be neglected in the general model as it typically is small for a well designed series elastic actuator.

3. Design of a Bowden-cable driven distributed series elastic actuator

The basic idea, in designing this actuator was to detach the actual motor from the robot frame by the use of flexible Bowden cables (Fig. 7) to minimize the mass of the exoskeleton, which is important for an impedance controlled exoskeleton.

The actuator system is constructed as a rotating joint, which has to function as a torque source. Such joints were integrated in the developed gait training robot (Fig. 1) as hip and knee joints. Both the flexion and the extension (bending and stretching motion) cable are a continuous unit (Fig. 7, sub 6). This was done for safety reasons. In case a cable breaks, its tension will be lost and no safety threat will occur to due unidirectional forces. This choice implies that the force transfer from the cables to the disc is friction based. The same applies to the cable connecting the springs; to prevent slipping, strips of high friction synthetic material have been fixed on the inside of the disk. Slippage would not affect the force output but could shorten the motion range.

The power transmission from motor to joint is realised by use of so called Bowden-cables. A Bowden-cable is a type of flexible cable used to transmit power by the movement of an inner cable relative to a hollow outer cable, generally a spiral steel wire with a plastic outer sheath, often containing an inner liner to reduce friction. Because Bowden-cables introduce orientation-, speed- and tension-dependent friction, friction compensation is needed. The angles of the curves in the cable and their radii appear to be the main determinants of the actual friction. Also wear and (pre-)tension of the cables are important factors. Because these parameters are hardly observable and their effects complexly interrelated, it is impossible to compensate the friction properly with feedforward control alone. Acceptable compensation may be achieved by introducing a feedback force control loop. This requires a force measurement located *after* the cable transmission.

We chose to use springs for force measurement. A spring can be considered as a compliant and relatively low-cost force sensor, as its length can be considered proportional with the force. Two compression springs were connected to the actuator disk with a cable so that a torque spring is created in between the actuator disk and the lower segment. The two compression springs are pre-tensioned with the maximally desired force, so that the connecting cable will always be under tension during operation.
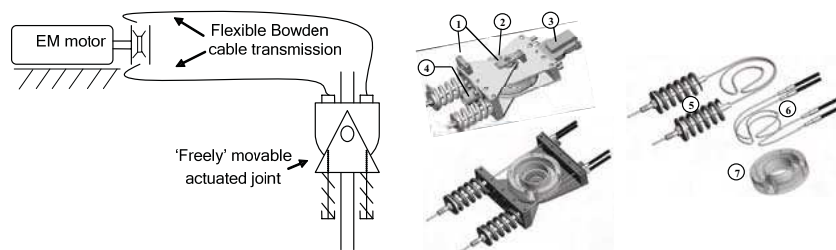

Fig. 7. Left a global lay-out of the proposed actuator system. The actuated joint can be lightweight as the motor is placed on the fixed world. On the right the final design of the joint alone is shown. The picture shows the actuated joint, the other side (not visible) of the Bowden cables is connected to a second disk driven by a servo motor; the latter side is situated on the fixed world. The cable with the two springs is the connection between the actuated disk and the joint output axis. Numbered parts: 1. sensor mounts, 2. joint end-stop, 3. upper connection side of the joint, 4. lower connection side of the joint, 5. set of two pretensioned compression springs, realizing a rotational spring around the main joint axis; the series elastic element of the actuator, 6. set of two pairs of uninterrupted Bowden cables, connected to the motor, transferring force to the actuator disk via friction. 7. actuator disc; this disc can rotate independently of both connection sides of the joint, or rather, it is connected to them via a force coupling, not an angle coupling.

The concept is similar to Series Elastic Actuation (SEA), treated extensively in (Robinson 2000). Its theoretical framework has to be only slightly adapted to be applicable on the actuator presented here. The differences with (Robinson 2000) are that we constructed a *rotational* joint instead of a linear, *integrated* the actuator with the robot-joint and added a *Bowden cable* transmission. *Common* cable drives have been used with SEA before, for example in the "Spring Turkey"(Pratt et al. 2001).

The Bowden cable transmission might negatively influence the bandwidth of the actuator compared to common SEA, as it introduces friction and compliance into the position control loop. On the other hand, it is possible to select a heavier motor, as the motor weight is of no

importance in this setting and a larger motor inertia will increase the bandwidth of the actuator, as a smaller gear-ratio, thus a smaller reflected mass can be used (Robinson et al. 1999).

Design parameters, besides the choice of motor and gearing, are the actuator disk diameter and the stiffness of the springs. The diameter is a compromise between the size of the joint and the low tension (thus friction) in the cables. The stiffness is a compromise of a high force control bandwidth versus minimal endpoint impedance combined.

The proposed actuator was designed and built to function as a knee joint. With this set-up (Fig. 7), the measurements were carried out. It has an approximate peak torque output of 30 Nm. Four Bowden cables of 1.5m each were used. An LVDT sensor was used for spring length measurement. The model of the distributed SEA is in essence the same as that of the SEA (Fig. 6). The main difference is the much higher friction due to the cable transmission and the elasticity in the cable transmission itself. Details can be found elsewhere (Veneman et al. 2006).

4. Performance of the actuators

The developed models were mainly meant for design purposes. The performance of the actuator can be considered independently of such model assumptions. In this chapter several issues are considered that determine the feasibility of the actuator for the described application (compare (Hayward and Astley 1996), (Morrell and Salisbury 1998)). Performance depends on many small constructive and sometimes controller decisions, so the outcome should be interpreted as a mere indication of the achievable performance with the presented type of actuation..

The performance will be considered in two consecutive issues:

1. Bandwidth of force tracking with a fixed load: Up to what frequency can the output force of the actuator be modulated with feedback control?
2. Reduction of the output-impedance: how well can the same controller decrease the mechanical output impedance of the actuator?

For the measurements with the distributed SEA a Bowden cable course has to be defined, as this affects performance. The optimal course of a Bowden cable would be straight, as bending introduces friction and backlash. A realistic standard situation was defined in which the Bowden cables are bent over 90° with a radius of 0.8 m..

4.1 Bandwidth of force tracking with fixed load.

To obtain acceptable force tracking feedback control is needed. The objectives of the feedback controller design were to improve the extent and accuracy of the force control, to reduce the apparent friction and inertia when back driven, and to reduce the sensitivity to load impedance variations. The force command was interpreted as a desired spring-length or pressure level, which then was controlled in a feedback loop, resulting in a torque command to the servomotor of the actuator or a current to the valves.

A tuned PID controller is the most straightforward choice, and can be designed based on the open loop behaviour of the plant and/or general tuning rules, like the ultimate cycle method of Ziegler and Nichols. This method has been used to tune feasible controllers.

Due to the amount of noise in the spring length measurement (LVDT) of the SEA, the differential action of the controller introduced a lot of noise into the control command. To prevent this, the encoder measurements of the motor position were used in the differential part of the controller.

The force tracking bandwidths were evaluated for force levels with increasing amplitude to investigate the effects of saturation. Force tracking transfer functions were identified using a

multisine signal with frequency content between 0.1 and 30Hz. The signal was crest optimized, to prevent appearance of high peaks in the composed signal.

4.2 Reduction of the mechanical output-impedance

In relation to the 'patient in charge'-mode it is important to determine the minimal mechanical output impedance. This is also called the back driveability of the device or actuator. The uncontrolled compliant actuators are already back driveable, but still have, depending on the actual configuration, high impedance.

The output-impedance is measured by imposing a position trajectory upon the load position (x_{load}) and measuring the actuator force. For the pneumatic actuator and the series elastics actuator this external position perturbation was opposed by DC motor. For the distributed SEA the external position perturbation was applied manually.

The hand was considered feasible as disturbance source, considered the intended application of the actuator.

5. Results

5.1 Pneumatic cylinder actuator

Bandwidth of force tracking with fixed load

The force-bandwidth of the PCA depends on the RMS of the amplitude of the reference input (Fig. 8) It appears that for low forces behaviour is predicted poorly by the model. This is probably due to the heavy influence of friction forces that were only basically modelled. Another possibility is that the measurement for small pressures is not accurate enough. For larger amplitudes the model appears to give at least a good indication of what the system can achieve. The reduction in the force tracking bandwidth for larger force levels are due to flow restrictions caused by the size of the inlet and outlet openings and the tube diameters and lengths. Larger inlet and outlet openings and tube diameters and shorter tubes reduce the flow restrictions and increase the force-tracking bandwidth for larger desired force levels.
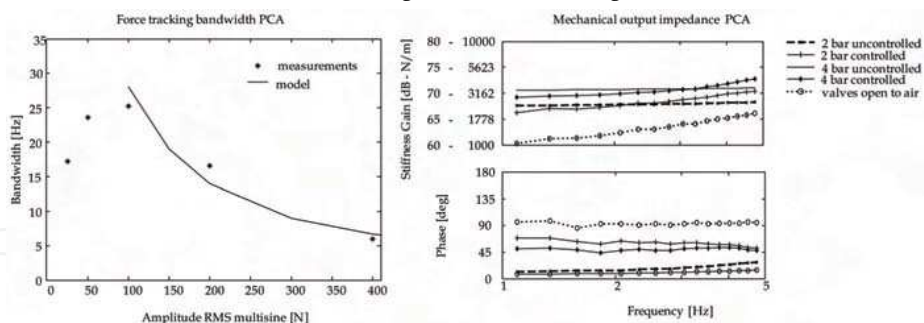

Fig. 8. Performance of the pneumatic cylinder actuator. Left: Force tracking bandwidth as function of reference RMS amplitude. Right: Measurement of controlled impedance. Bode plot of the force response to a 1-5Hz multisine motion profile. For comparison the uncontrolled values are added, together with the case in which both valves are switched open to open air.

Minimal mechanical output-impedance

To show the limits of impedance reduction in the pneumatic cylinder, some controlled (with reference F= 0 N) impedance responses are shown in Fig. 8. It appears that the impedance is

hardly reducible compared to the uncontrolled situation. The impedance response in case both cylinder chambers are open to the ambient is also shown. The impedance in this situation is caused by the friction of the system, together with the resistance to airflow in-/out-lets.

5.2 Series elastic actuator
Bandwidth of force tracking with fixed load

The closed loop force tracking depends on both the system transfer and on the implemented controller.As saturation plays a role already at very small RMS amplitudes of force, the actual force tracking is compared to force tracking in the model that included the saturation characteristics of the used motor. The transfer function of the non-linear model is determined in the same way as in the measurements by simulation with as input a force reference signal that was composed of multiple sinuses. The amplitude is given as RMS value of the multisine reference input.
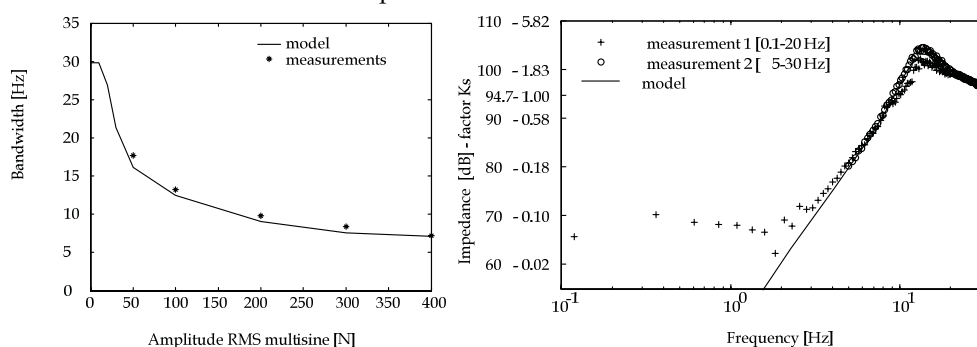

Fig. 9. Performance of the series elastic actuator. Left: Force tracking bandwidth as function of reference RMS amplitude. Right: gain of the controlled impedance transfer. For high frequencies the impedance becomes the stiffness of the springs, which is the intrinsic impedance. For low frequencies the model underestimates the impedance/stiffness. This is caused by the coulomb friction component, which gives the force response a lower limit.

We obtained a good agreement between model and measurements (Fig. 9). Similar as in the PCA saturation limits the bandwidth at higher desired force levels. From the same figure it can also be seen that the bandwidth demands, 12 Hz for small forces (below 100 N) and 4 Hz for large forces, are met

Minimal mechanical output-impedance

The controlled impedance depends on both system and controller. Here an example is given (using the PID same controller with reference value F= 0 N), to demonstrate some typical properties. In general the measurements were well predicted, except for low frequencies (<2 Hz). Where the model predicts a further decrease in impedance, the measurement indicates a lower boundary at about 5500 N/m. Further measurements showed that this was actually a lower boundary on the force output, which is caused by the coulomb friction component. Combined with certain motion amplitude, this results in the measured impedance boundary. For high frequencies the impedance approaches the intrinsic stiffness (K_s) that is the spring stiffness.

5.3 Distributed series elastic actuator

<u>Bandwidth of force tracking with fixed load</u>

The performance of the feedback controlled actuator with the implemented PID controller is presented in Fig. 10. Again the RMS amplitude of the input was varied.

It can be seen that the controlled bandwidth of the actuator is over 20 Hz for the measured range of torques in a normal Bowden cable course (Fig. 10 left). For smaller than 1 Nm torques the transfer falls off already at a lower frequency (not shown).

In case the cable is excessively bent, the effects of friction increase dramatically and cause a dramatic decrease of performance (Fig. 10 right).
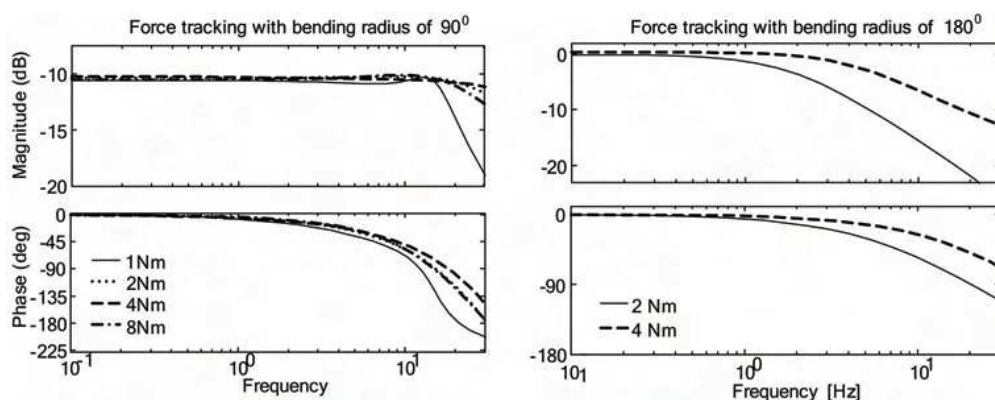
Fig. 10. Force tracking bandwidth of the distributed series elastic actuator. The RMS amplitude of the reference was varied. Left: the orientation was 90° with a bending radius of 0.8m. Right: the orientation was 180° with a bending radius of 0.4m.

<u>Minimal mechanical output-impedance</u>

The reduction of output impedance as achieved by using the PID controller with a zero reference force is shown in Fig. 11. From this Figure it can be concluded that a reduction of 10 – 13 dB (factor 3 – 4.6) of the mechanical impedance can be realized with feedback control in the frequency range of application. The values of the torques range from negligible up to 0.7 Nm for around 4 Hz motion. The noticeable effects of cable stick forces on the output force are also reduced. The time domain plot (Fig. 11 right) shows the small peaks caused by static friction compared to the overall torque response. Tests with a walking subject connected to this joint confirmed that the controlled impedance was low enough to experience unhindered lower leg motion. The minimal impedance was much smaller compared to the SEA since there was much less friction after the spring.

6. Discussion

6.1 modelling both SEA and PCA as elastic actuators

It was possible to model a series elastic actuator and a pneumatic cylinder actuator within one general framework of compliant actuation. This general model, as presented in Fig. 4., clearly shows the effect of the intrinsic stiffness (K_s) and controller design on the force tracking bandwidth, and on the controlled and uncontrolled mechanical output impedance. For the comparison of compliant actuators the intrinsic stiffness (K_s) of each specific actuator has to be defined, representing the average stiffness of the actuator during operation. In case

of the SEA K_s is the stiffness of the elastic element. In case of the PCA K_s was defined as the stiffness of the cylinder around its equilibrium position, at the pressure halfway in between ambient and buffer pressure, which will be about the average stiffness during operation. We found that saturation behaviour and output friction are very important in modelling elastic actuators as they greatly affect performance
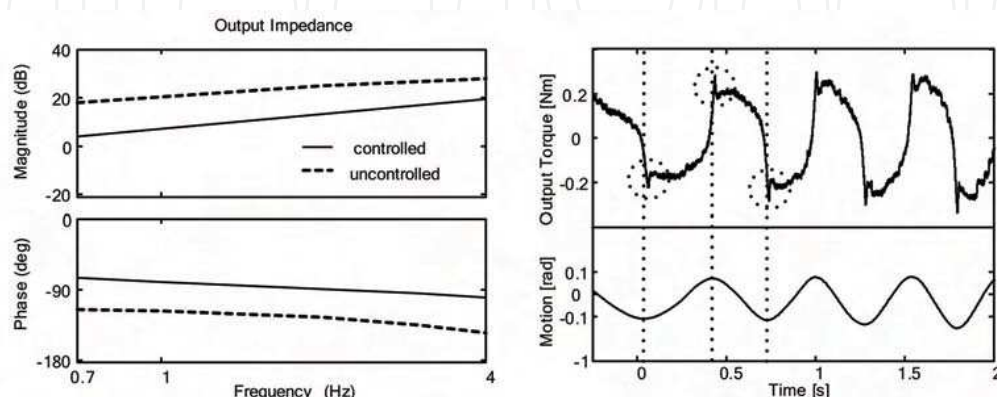

Fig. 11. Impedance of distributed SEA joint with compliance spring. Left: Bode plot of the impedance identifications of several measurement-series in both controlled and uncontrolled situations. The input motion disturbance signal was applied by hand. Only the frequency range with appropriate coherence is shown. Right: Typical torque response of the actuator to external motion, while controlled to zero force output. The small peaks are caused by stick, appearing when the motion is reversed.

6.2 Similarities and differences between SEA and PCA

Depending on its dimensions a PCA can be considered as a realisation of a 'compliant actuator'. Since PCA needs feedback linearization to be controlled properly, it appeared that it was much harder to predict and control a PCA than a SEA. The feedback linearization needs a precise actuator model, which in general will not be available beforehand. Important parameters, temperatures, actual buffer pressure et cetera, were left out of the modelling and will demand extra sensors if actual temperatures and the buffer pressure will be included in the feedback linearization. The PCA saturation behaviour was more complex than for the SEA. Therefore the design of a PCA demanded much more fine-tuning. The design and prediction of the performance of the SEA can be based on available data-sheet parameters.

The spring stiffness of a linear SEA with continuous force output of 500 – 1000N appeared to be in the order of 50-300 kN/m, resulting in a large force bandwidth of 4-10 Hz. The stiffness of the elastic element in our design was 54.5 kN/m. In a PCA the intrinsic stiffness is not constant; the range is defined by cylinder dimensions and the actual pressures and stroke position. The range of intrinsic stiffness of the selected cylinder during operation lies in between about 6 and 40 kN/m, depending on the feasible working range (Fig. 12). The effective stiffness as defined before is 11.3 kN/m. The effective stiffness of a PCA is on average roughly 20% of the designed linear SEA. Choosing the same low stiffness for the elastic element in a SEA would affect the large force bandwidth too much. The minimal stiffness/impedance of a SEA in the controlled situation is typically lower than the achievable stiffness/impedance of a PCA. When a PCA is controlled based on pressure measurements its minimal impedance is determined by both the

piston friction and the airflow resistance of the air in- and outlets. These properties depend on the cylinder and might be improvable by redesign, but can hardly be compensated by controller design. In the PCA, flow restrictions (relative small flow areas in cylinder, tubes) appeared to hinder a low-impedance control, i.e. the out-flow of the cylinder was mainly determined by these restrictions and not by valve control limitations. It may be possible to re-design a PCA for to minimize the mechanical output impedance. This might however affect system safety, as these small outlets serve as speed limiters. Since the friction is difficult to predict proper impedance control can only be achieved by adding a force sensor to the PCA. Another option would be designing pneumatic cylinders with a very low friction. These are commercially available in small size pneumatics, but to our knowledge not in the sizes needed for gait rehabilitation.
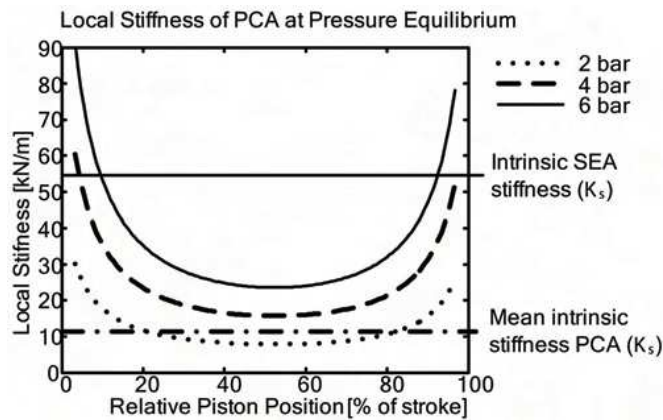

Fig. 12. Comparison between the stiffness of the series elastic actuator and the pneumatic cylinder stiffness.

Both the SEA and PCA can be designed to achieve a comparable force tracking bandwidth for 'midrange' force amplitudes. For smaller amplitudes the SEA outperforms the PCA in the achievable bandwidth and in accuracy, mainly due the smaller output friction. The force bandwidth for low amplitudes for the SEA was 30Hz and for the PCA about 25Hz. However, the SEA force bandwidth decreased faster with increasing amplitude (compare Fig. 8 and Fig. 9) Both actuators appeared to be impact proof due their intrinsic compliant behaviour at higher frequencies. The SEA appeared to be easier and better controllable in an impedance range at low frequencies, due less output friction, and due a more accurate force measuring.

6.3 Actuator performance of the distributed SEA

Using a basic PID controller the distributed SEA was able to achieve a force tracking bandwidth up to a bandwidth of 20 Hz and an expected large force bandwidth of up to 11 Hz. For small torque amplitudes and heavy Bowden cable bending this bandwidth decreased to as low as 2-3 Hz. This could to some extent be compensated for by increasing controller gain, which is possible as long no saturation for the motor is reached. Doing this in practise would demand a good observation of the bending radius of the cable since a return to the standard cable course or normal amplitudes could result easily in instability due to the decrease of physical friction. These problems can partly be avoided by constructing the robot in such a way that cables are never bent excessively. The decrease in bandwidth for (very) small torques is supposed to be an inherent limitation of the system and depends on the needed (pre-) tension in the cables and the bending

radius. Stick-slip compensating control strategies like dither signals, seem to be poorly applicable in Bowden cables. A feasible possibility could be a direct measurement of the friction forces, and including this measurement in the feedback controller.

The mechanical output impedance was shown to be considerably reducible by 10-13dB by feedback control compared to the impedance without feedback control. For our application a maximum torque of 0.7 Nm during 4 Hz imposed motion is acceptable. For gait rehabilitation practice such frequencies are high, and such torques are negligible. From the time domain plot it appeared that at every reverse of the velocity small torque peaks occur. Their size of about 0.1 Nm is however again negligible and acceptable for the application in a gait trainer robot.

Friction or stick was the most apparent non-linearity in the system. It was also shown that stick hardly distorted the controlled force output at frequencies below 15 Hz.

The spring stiffness affects actuator performance. We found that that a system with a stiffer spring has a higher bandwidth in open loop mode and is relatively less damped than with more compliant springs. When using stiffer spring we saw more non-linear distortions. This might be explained by the smaller motions of the motor that negatively affect the linearity of the relation between control command and motor torque. Spring deflections will be smaller when stiffer springs are used. As a result the non linear effects of backlash in the transmissions will then become more manifest.

Spring stiffness variations showed that both a too stiff and a too compliant spring can worsen performance. A stiff spring reduces the maximum allowable controller gain. The relatively low control gain then causes a larger effect of stick in the force output, resulting in a less smooth output in general. Low spring stiffness, on the other side, decreases the bandwidth of the system as demanded displacements, velocities and accelerations increase, which will saturate at a certain level. For every specific application this trade-off has to be made. In the design phase the required bandwidth or the amount and implication of stick might not be known beforehand. However springs can easily be exchanged.

The presence of the compliant element allows for a much higher position control gain, implying a better internal error rejection (Robinson 2000). Furthermore stability can be assured if the controller is tuned to the realistic cable situation with the least friction, so that changing the cable situation will increase the friction, which will lower performance but not result in instability. Friction forces always stabilize a system and the possible source of instability can only be overcompensation. This can be concluded considering a Lyapunov-stable linear system; if extra non-linear friction is added, more energy will be dissipated from the system, so that it will stay Lyapunov-stable.

Improvements of the actuator system could be realized by reducing system complexity, size and weight and by controller improvements. The complexity of the system can be slightly reduced by using two (thicker) Bowden cables instead of four. This has been tested and appeared to be equivalent in performance. Also the LVDT sensor has been replaced by a linear slider potentiometer, which is both smaller and cheaper. Possibly a torsion-spring element could be constructed instead of the two compression springs, which would reduce size and weight. Feasible commercial torsion springs however were not found. The controller outline could be changed to deal better with the specific non-linearities, like the so called 'late motor processing' as described in (Pratt et al. 2004), or by using voltage/velocity control instead of current/torque control. Finally, the joint could be redesigned to optimize the cable replacement procedure, and durability tests should be done to determine the needed frequency of cable replacement.

7. Conclusions

The designed SEA was slightly superior to the PCA for the described application in a gait rehabilitation robot, based on performance metrics. Other disadvantages of the PCA are the typical noise, dependency on pressurized air facilities and the complexity of the needed controller, which affects the robustness of the system. The SEA and PCA we evaluated were dimensioned to actuate a gait rehabilitation robot. From the evaluation of both type of actuators it can be concluded that both can be designed to meet power and bandwidth requirements, resulting in actuators of comparable weight and size.

However, due the high weight neither one system can be considered truly optimal for use in exoskeleton-type rehabilitation robot. To minimize the weight we designed and evaluated a new Bowden-cable-based series elastic actuation system. A robot joint containing this actuation system was constructed. It was shown that the performance demands of realizing a safe, lightweight, adjustable and powerful torque source were met. A force bandwidth of up to 20 Hz appeared feasible for small forces, when extreme cable bending was avoided. Lower bandwidths were found for higher forces, as a consequence of saturation ranging from 6-10 Hz. This meets the requirements we derived for the control of human gait using an impedance controlled exoskeleton. Distributed series elastic actuation appeared also suitable for low impedance control to facilitate unhindered motion, with maximal torque peaks of 0.7 Nm at 4 Hz motions on a scale of a 30 Nm actuator (less than 2.5%). This implies that a robot using these joints would be able to be used in both a high impedance 'robot-in-charge' as well as in a low impedance 'patient in charge' task for rehabilitation robots, as far as joint and actuator performance are considered.

Beside this typical application in the LOPES project, the principle of actuation could find wider use in all kinds of exoskeleton-like kinaesthetic interfaces. Of course dimensions should be optimized for every specific application.

The developed distributed series elastic actuator system showed that the principle of Series Elastic Actuation can be applied using a heavy friction transmission like Bowden cables. Despite the power loss and the introduced heavy friction, the actuator still functions well as Series Elastic Actuator. Heavier motors can be selected since they are detached from the actual robot construction. The friction of Bowden cables can well be compensated with feedback control.

8. Acknowledgement

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Mobile Robots: towards New Applications

Edited by Aleksandar Lazinica

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