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Relocating Actuators Towards a Base Frame Does Not Improve Weight and Inertia Characteristics in Our Upper-Extremity Exoskeleton

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Abstract— **In rehabilitation exoskeletons, alignment of robot and human joints is essential for comfort and performance. Most exoskeletons have their actuators directly at the DOF they control, despite performance being assisted by low movement inertias. For our new upper-extremity exoskeleton, we explored using a parallel robot for the auto alignment of the shoulder axes and three serial links to drive the rotations. We hypothesized that weight and inertia can be reduced by relocating the actuators to the non-moving base of the device, as others have done before. To investigate if this is indeed beneficial, we evaluated all possible topologies for placing motors and gearboxes and are here reporting on the best candidates. We explored several drive trains that combine coaxial axes and angular transmissions. As bevel gears show backlash, are high in weight and large in size, three alternative angular transmissions were investigated. After combining the new angular transmissions with the possible topologies and evaluating the 16 resulting combinations, we concluded that for our new, high-performance exoskeleton, the most optimal topology still is one with the motors and gearboxes placed directly at the joint. The hypothesis therefore was disproven for our usage scenarios.**

Fig. 1. A potential design for our new exoskeleton that uses a friction transmission: one of the 16 subconcepts that have been investigated in this paper.

I. Introduction

Stroke is a major cause for death and disabilities throughout the world [1], [2]. Common symptoms are pain in the shoulder, a decrease of range of motion, loss of motor coordination and a loss of sensory feedback [2]. Research has proven that intensive sensorimotor training using repetitive novel movements is effective [3]–[5]. And using robots for such training results in as good as or better results compared to the standard training [6], [7].

At the University of Twente, we are developing a new auto-aligning exoskeleton for the upper extremities that improves upon our earlier designs [8]–[10]. A potential design for this new device is depicted in Fig. 1. The exoskeleton will be able to control the shoulder, elbow, wrist and fingers individually, and will be used to do both unimpeded assessment and neural system identification. Stroke patients often suffer from abnormal movement coordination which might be caused by abnormal synergy between muscles [11]. To investigate this synergy, the ability to control the torques in each joint independently and over a large range of motion is essential. A strong exoskeleton robot is ideal for this purpose.

One challenge when using an exoskeleton is to keep its axes aligned to the human joints. The shoulder girdle has proven to be an especially difficult joint to keep aligned, as the humerus rotation center translates involuntary upwards with arm elevation [12]. Several mechanisms have been proposed to solve this, most of which use additional structures to keep the axes aligned [10], [12], [13]. For auto-alignment of the shoulder in the new robot, we will use an additional delta robot to allow translations and rotations in the shoulder to be decoupled. In [10] several structures for decoupling were compared. For translations the delta robot showed to have the best ratio of torsional stiffness to mass. Therefore, in this study the use of the delta robot is a given.

The exoskeleton should be able to be both stiff and compliant. Compliance is needed for performing free motions while not feeling the dynamics of the machine. Stiffness is necessary for applying sudden position perturbations. Measuring the neural reaction after such a perturbation helps understanding underlying pathophysiological mechanisms and discover the cause of the problems in the synergy between muscles of stroke patients. [14]–[16].

To achieve both stiff and compliant behavior, a stiff robot that uses admittance control will be used [11], [17]. Admittance control has excellent haptic interaction [18] as well as the ability to instantly switch from free motion to stiff perturbations [11]. Also admittance control can reduce the apparent inertia in the control loop to a certain degree.

As the apparent mass can only be reduced to a certain degree and often this reducing comes at the cost of higher

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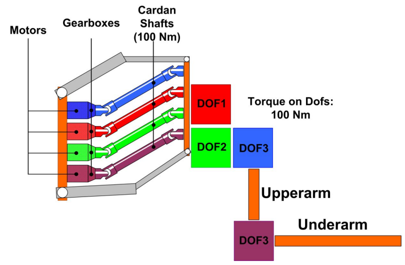
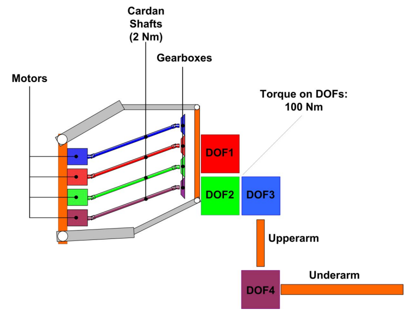
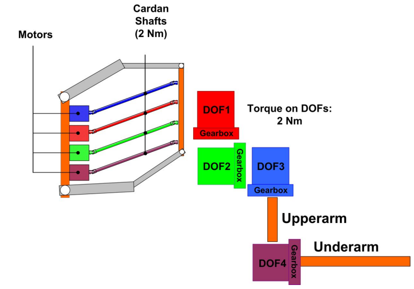


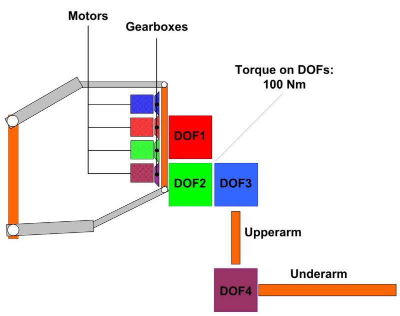
(a) Motors on base, gearboxes on base (T1-MBGB).



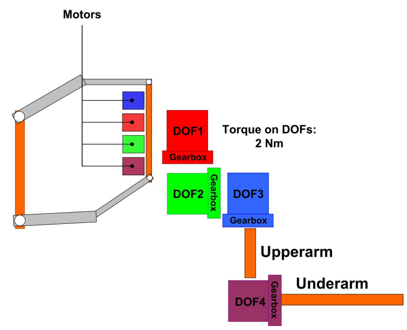
(b) Motors on base, gearboxes on head (T2-MBGH).



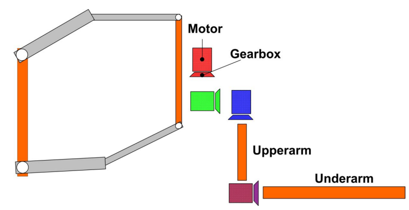
(c) Motors in base, gearboxes local (T3-MBGL).



(d) Motors on head, gearboxes on head (T4-MHGH).



(e) Motors on head, gearboxes local (T5-MHGL).



(f) Motors and gearboxes local (T6-MLGL).

Fig. 2. Possible topologies for motors and gearboxes. On the left of every figure is a delta robot. On its head a 3-DOF serial linkage, representing the shoulder joint, is placed. The fourth DOF in the picture is the elbow joint. Torques in the figure are based on an output torque of 100 Nm and a gearbox ratio of 50:1.

demands on actuators and control loop, reducing the moving mass and inertia while maintaining structural stiffness, will enhance the performance of the robot. This might be achieved by relocating actuators and gearboxes to a non moving base. A careful assessment should be made whether the possible decrease in mass from moving these components weighs up against the possible increase in complexity due to for example the need of a drivetrain. Therefore, the goal of the current paper is to determine if an alternative topology for the motor, gearbox and drive-train would lower the weight and inertia of the exoskeleton shoulder, and thereby assist in achieve its performance requirements.

Therefore, the aims of this paper are to determine:

- which mechanisms allow torques to be transferred from a relocated actuator position,
- if the weight of the exoskeleton joint can be minimized by relocating actuators and gearboxes,
- how changing the position of motor and gearbox changes the design compared to conventional exo-skeletons.

Based on previous work and experience, we are designing the new robot to be able to translate in a workspace of a cubic 300x300x300 mm and to rotate 360^o in every direction. In each direction it should be capable of handling torques of 100 Nm. These maximum torques should lead to a maximum deflection of the endeffector of 5 mm and maximum angular deflections of the drivetrain of 1^o per 100 Nm.

This study summarizes the full overview given in [19], with most attention given here to the two topologies with the best performance.

II. Topologies

The basis for finding the optimal design are the six topologies in Fig. 2. The different topologies show the possible locations for the motors and gearboxes in the 6-DOF shoulder exoskeleton. The delta robot is displayed on the left of every figure. On the head of the delta robot, a 3-DOF serial mechanism is placed that rotates the shoulder. A serial mechanism is needed here, as all rotational mechanisms using parallel linkages do not have a large enough range of motion for our shoulder exoskeleton. In the topologies, the motors and gearboxes can be placed in the base of the delta robot, at the head of the delta robot but before the rotational mechanisms, or locally at the driven axis itself.

When the motors are placed in the base, a solution must be found in order to translate the torque from the remotely placed motors to the axis they need to rotate. As the shoulder mechanism that will be used is a serial linkage, each DOF rotates all the next DOFs in the series. This also means that the first DOF will change the orientation of the second DOF. Therefore the remote actuation mechanism for the second DOF needs to be able to rotate around the axis of the first DOF as well as the axis of the second DOF. Here we have chosen to use coaxial axes with angular transmissions. An example of how such a coaxial design would look like for a

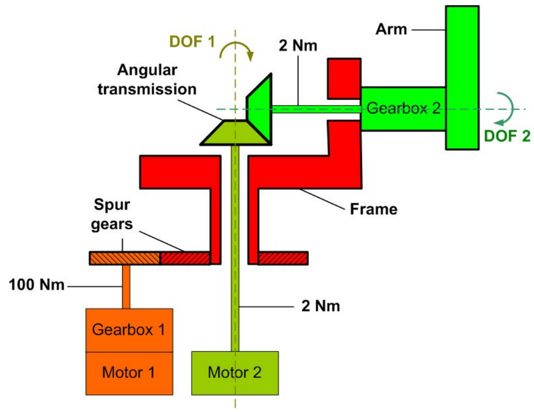


Fig. 3. Illustration of remote actuation using coaxial axes. In this figure two topologies are displayed: Motor 1 is placed on the base or on the head and has its gearbox at the same position as the motor. Motor 2 has the motor placed at the base or on the head and the gearbox is placed local. As can be seen, placing the gearbox local changes the loading on the shafts and gears. (The gearboxes in the figure have a ratio of 50:1).

simple 2-DOF situation is shown in Fig. 3. Other solutions using for example flexible shafts or cables are either not stiff enough or have other theoretical and practical limitations.

In Fig. 3, the way to cope with the translations of the delta robot and the way to translate the torque from the base to its head are not shown. To allow fine control with minimal vibrations a solution that rotates at a constant velocity is needed. For this, double cardan shafts (propeller shafts) are preferred over other constant velocity shafts as they have a much simpler design that can be manufactured fairly lightweight. Rzeppa joints or Thompson couplings might have better constant velocity properties, but they are also significantly heavier.

The angular transmission in Fig. 3 is needed as the two DOFs are perpendicular. A common solution for angular transmission is the use of bevel gears. These however show backlash and are fairly heavy. Therefore other ways to get the perpendicular transmission to work are needed. Alternatives are investigated as well as how these combine with the six topologies in Fig. 2. This is the basis for the subconcepts that are presented in the next section.

The topologies affect how the parts in the construction are loaded. Parts in front of the gearbox will be loaded by a reduced torque but rotate at higher speeds. In Fig. 2, the parts that are loaded with the high and reduced torque are marked.

III. Subconcepts

A subconcept consists of a topology picked out of Fig. 2 in combination with an angular transmission. Three possible angular transmissions will be presented in section III-B: bevel gears, friction drives, and cable drives. Topology T6-MLGL is an exception on this approach. As this is the topology with the motors and gearboxes placed local, cardan shafts and angular transmissions are not needed. Only one subconcept is needed for this topology. All the other subconcepts do need a drivetrain. This is displayed in Tab. I.

A. Gearboxes and motors

Placing motors in the base will lead to different requirements than placing motors locally at the DOF they control. Placing motors locally requires low weight, compact motors and gearboxes whereas this is less important when they are placed in the base. For convenience it is assumed that the motors and gearboxes for every concept will be the same. The high demands for having motors placed locally will be used. From a control perspective backlash should be limited as this could lead to instabilities of the admittance control scheme. Friction, often a non negligible factor in gearboxes, is not a big problem as this can be compensated for by the control loop.

As admittance control will be used, having zero backlash is important. Harmonic gear drives have zero backlash and have small dimensions with low mass. Therefore these will be used as a gearbox. The maximum delivered torque was set at 100 Nm, a harmonic gearbox from Harmonic Drive AG (CPL-2A-25) with a ratio of 50:1 can handle this torque.

As stated in Sensinger [20] outrunners are a good choice as a motor in robotic applications in which both high torques as well as high accelerations are needed. Although the inertia of the outrunner might be higher than conventional commercial brushless motors this is compensated for as the outrunner can deliver more torque at a lower rpm. Therefore an outrunner will be used. An estimation of the size and mass can be made by combining data from catalogs and from experts from the field. The motor is estimated to be a cylinder with a diameter and height of 60 mm. It needs to handle a power of 2 kW and be capable of delivering 2 Nm of torque. The weight is estimated at 550 g.

B. Angular transmissions

As existing angular transmissions using bevel gears show backlash, are fairly heavy and big, alternatives were investigated. Two alternatives were found: friction drive and spatial cable drive. A small description will be given here, detailed information can be found in [19].

1) Friction drive: Friction drives work by pushing two gears together. When turning one gear the generated friction force will transmit the torque from one gear to the other. For this study the required normal force is generated by using a spring washer. By controlling the deformation of this washer the normal force can be changed. An important feature of friction drive is that they have a maximum torque they can transmit. Exceeding this maximum will lead to slippage between the gears. For use in an exoskeleton this property can be used as a failsafe against overloading the patient. Other features from friction drive are stated in [21]: They can operate with negligible backlash, they produce low noise and hardly any vibration and can operate very smoothly at high speeds. In Fig. 4 the drivetrain of an exoskeleton using friction drives is shown.

2) Cable drive: Cable driven gears do not suffer from torque ripple, allowing a smooth transmission. When properly installed they have no backlash [22]. A big advantage of using cables is the ease in which torque can be transmitted

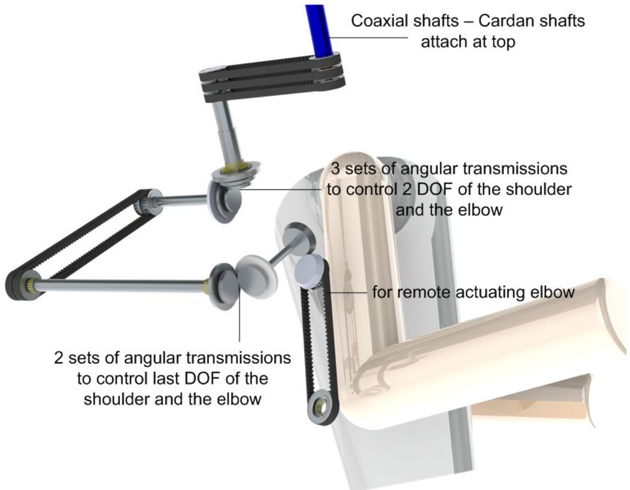


Fig. 4. Friction based drivetrain ('friction drive') that transfers torques through the shoulder structure via friction between perpendicular disks. Note that to align the axes with the rotation center of the shoulder, significant rerouting of the drivetrain is required.

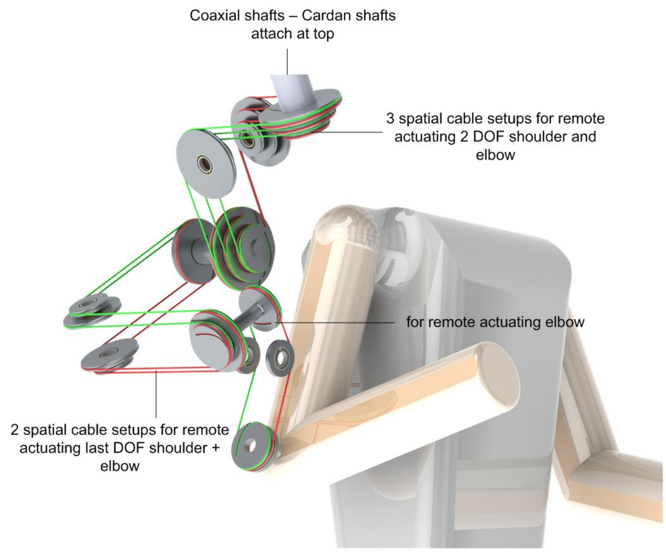


Fig. 5. Cable based drivetrain ('cable drive') that transfers torques through the shoulder structure via cables between perpendicular disks. Note that to align the axes with the rotation center of the shoulder, significant rerouting of the drivetrain is required.

over long distances. Example of an exoskeleton using this principle is the Caden-7 [23]. It has its motors placed on a remote base, cables transfer the torque from the motors to the joint they control. For limited ranges of motion, smart wrapping using helical grooves allows the cables to roll from one gear to the other without inducing length-change stresses or cable-on-cable friction. When using pulleys, the two driving gears can be placed separately from each other. This is useful as in most exoskeletal shoulder designs there needs to be some distance between the gears to avoid collisions or intersections with the human body. For driving in two directions two cables are needed. In Fig. 5 the drivetrain of an exoskeleton using spatial cable drives is shown.

C. *Quick Evaluation*

To achieve our goal of remote actuation, the 16 potential subconcepts are evaluated. To reduce this amount a selection is made on size and mass. The results are given in Tab. I. Topologies T1 to T5 need an drivetrain and therefore have no workable solutions with no transmission. Topology T6 does not need a drivetrain as the motors are placed locally. An analysis of the topologies using bevel gears showed that when the gears are further in the drivetrain than the gearboxes (therefore loaded with 100 Nm of torque) the gears need to be big and therefore heavy. The shafts of the drivetrain also contribute significantly to the total weight and inertia. Therefore topologies T1, T2 and T4 were discarded. Topology T3 and T5 showed to have the exact same topology when using gears or friction drive. As friction drive has superior qualities over bevel gears the topologies using bevel gears were discarded. The topologies using friction transmission with the gears that are loaded with 100 Nm of torque (T1, T2

TABLE I

SUMMARY OF EVALUATION OF SUBCONCEPTS FOR ALL TOPOLOGIES (SEE SEC. III-C)

Motor	Base			Head		Local
Gearbox	Base	Head	Local	Head	Local	Local
Type	T1-MBGB	T2-MBGH	T3-MBGL	T4-MHGH	T5-MHGL	T6-MLGL
Angular Transmissions						
None	Not an option as each of the subconcepts T1-T5 needs an angular transmission					**Evaluated in Sec. III-D**
Bevel gears	Too heavy due to high torque requirements in universal shafts and bevel gears	Too heavy due to high torque requirements in bevel gears	Friction drive has same topology with better transmission characteristics	Too heavy due to high torque requirements in bevel gears	Friction drive has same topology with better transmission characteristics	No drivetrain needed when motor and gearbox are placed locally
Friction drive	Too heavy due to high normal forces		**Evaluated in Sec. III-D**	Too heavy due to high normal forces	T3-MBGL has substantially lower mass	
Cable drive	Too heavy and too big due to high torque requirements		Too limited range of motion for required multiturns	Too heavy and too big due to high torque requirements	Too limited range of motion for required multiturns	

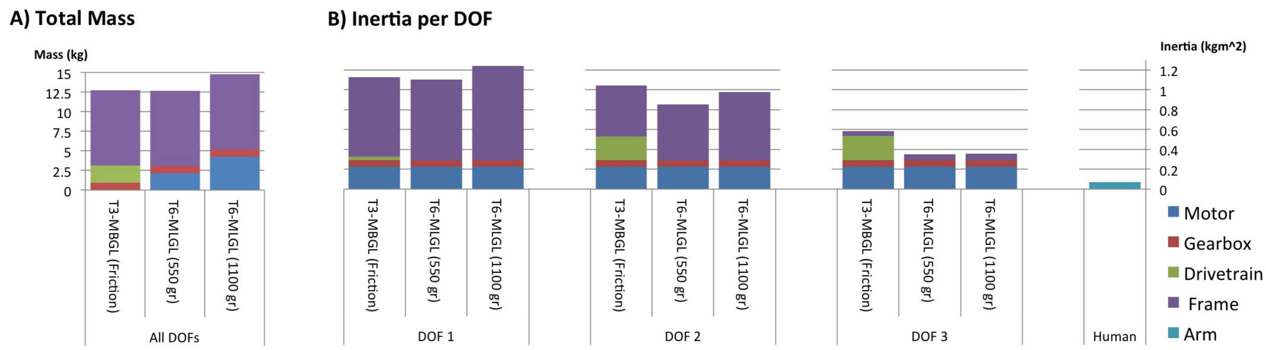


Fig. 6. A: Total mass of the two remaining configurations. Also shown are the parts of the configuration that contribute to the total mass. On the left the situation is displayed when the motor weighs 550 g, on the right this is displayed for the 1100 g situation. When motors weigh 550 g the T3-MBGL weights slightly more. When the motor weight is increased to 1100 g the T3-MBGL shows to be significantly more lightweight. B: Inertia per DOF and contributions of the subparts to the total inertia. As can be seen, the inertia for the T3-MBGL is higher than T6-MLGL every time. The drivetrain negatively compensates for the inertia saved by not having a motor placed locally. For the second and third DOF the drivetrain even contributes significantly to the total inertia as its inertia gets multiplied by the ratio of the gearbox squared.

and T4) showed to need too much normal force to transmit this torque without slippage. The high normal force would set high demands on the surrounding structures, therefore these topologies were left out of further investigation. Topologies T3 and T5 both are plausible concepts. However topology T5 closely resembles T3, a more detailed analysis showed that the T5 topology will be significantly heavier as the motors move around. Therefore concept T3 will be the more optimal design and T5 is discarded. (Extensive detailing of the above can be found in [19].)

The reduction leaves two concepts for the final evaluation: T3-MBGL using friction drive and T6-MLGL, the concept that is most used in current exoskeletons with motors placed right before the joint they control.

D. Final Evaluation

From the remaining concepts detailed models have been made in Solidworks. Using these models the total mass and inertia can be determined. It is assumed that both final concepts will use the same frame for holding the motors and gearboxes. This frame is optimized for the design using friction transmission as this design sets the most requirements on the design of the frame. As it needs a drivetrain the beams of the frame should be straight so that these can support the shafts of the drivetrain. Using the same frame for the T6-MLGL concept leads to a non optimized design for this concept (for a more in-depth discussion see [19]).

In Fig. 6a the masses of both remaining concepts are given. As the assumed weight for the outrunner motors might be on the low side two analyses have been done. One with a motor of 550 g, the other where the motor is 1100 g. For the T3-MBGL concept there is no difference between these two analyses as the motor is on the non moving base. e Surprising is that there is hardly any weight saving when relocating motors to the base. The drivetrain adds the same amount of weight that is saved by relocating the motors. When the motors weigh 1100 g the effect of relocating the motors to the base is bigger. In this case relocating leads to an improvement.

In Fig. 6b the inertias of the final concepts are given. The given inertias are equivalent inertias felt at the arm of the patient. It is assumed that when increasing the weight of the motors, the inertia of actuating the motors in unchanged. It does however have an effect on the inertia of moving the motors around. This effect is included in the frame part. As the T3-MBGL has non moving motors there is no difference in inertia when using heavier motors using the just stated assumptions. Having a higher total mass would not be a problem if this weight would be better distributed over the total design. It was hypothesized that a drivetrain would do this. However looking at Fig. 6b gives a different image.

The inertia of the T3-MBGL concept is higher on almost every DOF for both the low mass of the motor as the high mass. Looking at the figures this can be explained by the contribution of the drivetrain. This is only a little for the first DOF but increases for the subsequent DOFs. The high contribution can be explained by looking at the definition of the equivalent inertia. The equivalent inertia at the output of a gearbox is calculated by multiplying all the parts at the input by the gearbox ratio squared: in this case this leads to an amplification of 2500. Decreasing the gearbox ratio might lead to a reduced equivalent inertia however decreasing the gearbox ratio would also lead to an increased load on the components. These would therefore need to become bigger and the gearbox ratio has to be decreased again. The effect of reducing the gearbox ratio was therefore estimated as not significant and could even be negative.

IV. DISCUSSION AND CONCLUSION

This paper set out to optimize the motor, gearbox and drivetrain topologies in a 6-DOF self-aligning exoskeleton shoulder. It is hypothesized that relocating heavy parts as gearboxes and actuators to a non moving base can reduce the moving weight and inertia. From 16 possible options two feasible lightweight shoulder designs can be deduced. The first one uses motors that are relocated to the non moving base of the delta robot. As the motors are in the base a drivetrain is needed to get the torque from the motor to the actuated DOF. This is done by using friction transmission. During this study, the friction drive showed to have excellent properties compared to other ways of angular transmission that have been found. The other remaining design uses a more conventional exoskeletal design where the motors are placed local, just in front of the part they control.

Analyzing these two concepts leads to the conclusion that when using very lightweight outrunner motors (550 g) for actuation of the exoskeleton, relocating motors and gearboxes towards the base is not the best solution.

The concept with motors placed locally has a lower weight and lower inertia than the concept with the relocated motors on every DOF. It scores better while it uses a frame that is optimized for the concept with the remotely placed motors. Therefore it can probably score even better.

As the estimation of the weight of the outrunner motors might be on the low side another analysis has been done using motors of 1100 g. It was found that then relocating motors, compared to having motors locally, saves around 2 kg on the total weight.

Looking at inertias, the concept with the relocated motors has a lower inertia for the first DOF, at other DOFs the motors placed local still scores better. The slightly higher inertia of the first DOF can probably be improved by optimizing the frame design for the concept with the motors placed local. Moreover even if the concept with relocated motors performs slightly better, placing the motors local might still be a better choice because of its simplicity. The need of a drivetrain when relocating the motors, greatly increases the number of needed parts. Not only can all these parts be sources of disturbance, they also increase the chance of a failure.

As the frame for both concepts is a big contributor to the total mass, it is probably more worthwhile to invest in finding the most optimal configuration of the axes of the exoskeleton in combination with an optimized frame than focusing on relocating actuators and gearboxes. More can be gained when using motors placed locally on redesigning the shoulder as it allows for more configurations and more flexibility in frame design.

Having a drivetrain sets serious restrains on both the configurations that can be used and on the shapes that can be picked for the frame. Therefore for the exoskeleton proposed in this study the most optimal motor, gearbox and drivetrain topology is placing the motor and gearbox local just in front of the DOF they control.

REFERENCES

[1] J. G. Broeks, G. J. Lankhorst, K. Rumping, and A. J. Prevo, "The long-term outcome of arm function after stroke: results of a follow-up study.," *Disabil Rehab*, vol. 21, pp. 357–64, Aug. 1999.

[2] J. Adamson, A. Beswick, and S. Ebrahim, "Is stroke the most common cause of disability?," *J Stroke Cerebrovasc Dis*, vol. 13, no. 4, pp. 171–7, 2004.

[3] S. Barreca, S. L. Wolf, S. Fasoli, and R. Bohannon, "Treatment interventions for the paretic upper limb of stroke survivors: a critical review.," *Neurorehab Neural Repair*, vol. 17, pp. 220–6, Dec. 2003.

[4] R. Van Peppen, G. Kwakkel, S. Wood-Dauphinee, H. Hendriks, P. Van der Wees, and J. Dekker, "The impact of physical therapy on functional outcomes after stroke: what's the evidence?," *Clin Rehab*, vol. 18, pp. 833–862, Dec. 2004.

[5] G. Kwakkel, R. van Peppen, R. Wagenaar, S. Wood-Dauphinee, C. Richards, A. Ashburn, K. Miller, N. Lincoln, C. Partridge, I. Wellwood, and P. Langhorne, "Effects of augmented exercise therapy time after stroke: a meta-analysis," *Stroke*, vol. 35, pp. 2529–39, Nov 2004.

[6] A. C. Lo, P. D. Guarino, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, D. G. Federman, R. J. Ringer, T. H. Wagner, H. I. Krebs, B. T. Volpe, J. Bever, C. T., D. M. Bravata, P. W. Duncan, B. H. Corn, A. D. Maffucci, S. E. Nadeau, S. S. Conroy, J. M. Powell, G. D. Huang, and P. Peduzzi, "Robot-assisted therapy for long-term upper-limb impairment after stroke," *New Engl J Med*, vol. 362, no. 19, pp. 1772–83, 2010.

[7] T. H. Wagner, A. C. Lo, P. Peduzzi, D. M. Bravata, G. D. Huang, H. I. Krebs, R. J. Ringer, D. G. Federman, L. G. Richards, J. K. Haselkorn, G. F. Wittenberg, B. T. Volpe, C. T. Bever, P. W. Duncan, A. Siroka, and P. D. Guarino, "An economic analysis of robot-assisted therapy for long-term upper-limb impairment after stroke," *Stroke*, vol. 42, no. 9, pp. 2630–2, 2011.

[8] A. Stienen, E. Hekman, F. van der Helm, G. Prange, M. Jannink, A. Aalsma, and H. van der Kooij, "Dampace: dynamic force-coordination trainer for the upper extremities.," in *Proc 10th ICORR'07*, 2007.

[9] A. Stienen, E. Hekman, G. Prange, M. Jannink, A. Aalsma, F. van der Helm, and H. van der Kooij, "Dampace: design of an exoskeleton for force-coordination training in upper-extremity rehabilitation.," *ASME J Med Dev*, vol. 3, no. 031003, pp. 1–10, 2009.

[10] A. Stienen, "Self-aligning exoskeleton axes through decoupling of joint rotations and translations," *IEEE Transactions on Robotics*, vol. 25, no. 3, pp. 628–633, 2009.

[11] A. H. A. Stienen, J. G. McPherson, A. C. Schouten, and J. P. A. Dewald, "The ACT-4D: a novel rehabilitation robot for the quantification of upper limb motor impairments following brain injury.," *Proc 12th ICORR'11*, vol. 2011, p. 5975460, Jan. 2011.

[12] T. Nef, R. Riener, R. Müri, and U. P. Mosimann, "Comfort of two shoulder actuation mechanisms for arm therapy exoskeletons: a comparative study in healthy subjects.," *Med Biol Eng Comp*, Feb. 2013.

[13] A. Schiele and F. C. T. van der Helm, "Kinematic design to improve ergonomics in human machine interaction.," *T Neural Sys Rehab Eng*, vol. 14, pp. 456–69, Dec. 2006.

[14] E. de Vlugt, A. Schouten, and F. van der Helm, "Quantification of intrinsic and reflexive properties during multijoint arm posture.," *J Neurosci Methods*, vol. 155, pp. 328–349, Sep 2006.

[15] J. b. McPherson, A. c. Stienen, J. Drogos, and J. b. d. Dewald, "The relationship between the flexion synergy and stretch reflexes in individuals with chronic hemiparetic stroke," in *Proc 12th ICORR'11*, (Zurich), 2011.

[16] R. Trumbower, V. Ravichandran, M. Krutky, and E. Perreault, "Altered multijoint reflex coordination is indicative of motor impairment level following stroke," in *Proc. 30th EMBS 08*, (Vancouver), pp. 3558–3561, Aug 20-24 2008.

[17] R. van der Linde and P. Lammertse, "Hapticmaster - a generic force controlled robot for human interaction.," *Ind Robot*, vol. 30, no. 6, pp. 515–524, 2003.

[18] R. Q. Van Der Linde, P. Lammertse, E. Frederiksen, and B. Ruiter, "The HapticMaster , a new high-performance haptic interface," tech. rep., FCS Control Systems, 2001.

[19] A. Philippi, S. Ates, H. van der Kooij, and A. H. A. Stienen, *Towards an Optimal Design of a 6-DOF Self-Aligning Exoskeleton Shoulder Joint*. Master thesis, University of Twente, 2014.

[20] J. W. Sensinger, S. D. Clark, and J. F. Schorsch, "Exterior vs. Interior Rotors in Robotic Brushless Motors," *ICRA'11*, vol. 60611, pp. 2764–2770, 2011.

[21] S. Loewenthal, D. Rohn, and B. Steinetz, "Application of traction drives as servo mechanisms," *NASA, Lewis Research Center*, vol. N85-33520, pp. 119–139.

[22] W. T. Townsend and J. A. Guertin, "Teleoperator slave - WAM design methodology," *Industrial Robot*, vol. 26, no. 3, pp. 167–177, 1999.

[23] J. C. Perry, J. Rosen, and S. Burns, "Upper-Limb Powered Exoskeleton Design," *T Mechatron*, vol. 12, pp. 408–417, Aug. 2007.